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FEASIBILITY ASSESSMENT OF THE PARTICULATE-PACKED, THIN-WALLED CONTAINER

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ABSTRACT

The Thin-Walled, Particulate-Packed container was designed as one of several container concepts intended for the disposal of used fuel bundles from CANDU Nuclear Power Generating Stations. The concept has been shown to present a viable option for such disposal. This viability was demonstrated in an extensive set of tests conducted on a full-scale prototype and supported by preliminary tests and analyses. The prototype was found to be well designed and manufactured to adequate standards. It was found to have adequate strength to support an external pressure of 10 Mpa at temperatures up to 150°C. The container was assembled without significant difficulty. Deformations measured following the hydrostatic tests suggest that the particulate was packed well. Significant settlement occured during transportation of the container from Toronto, Ontario to Whiteshell, Manitoba. This large, uniform void did not cause the container failure. The particulate's strength and creep resistance were found to be acceptable. The results of the tests and analyses are presented in this report.

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The concept of the thin-walled container internally supported by a vibratory compacted granular material (particulate) was introduced by Whiteshell Nuclear Research Establishment (WNRE) in 1978. The detailed design was developed by the Mechanical Design Department of Ontario Hydro. The Ontario Hydro Research Division (OHRD) provided consulting services and analytical and testing resources. The hydrostatic test program was conducted by the OHRD at WNRE facilities with technical and administrative support provided by WNRE personnel.

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EXECUTIVE SUMMARY

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The concept for the disposal of used fuel bundles from CANDU Nuclear Power Stations is based on the emplacement of bundles in containers which are then emplaced in a deep underground vault in plutonic crystalline rock. The Thin-Walled, Particulate-Packed (TWC) container is one of several disposal container options currently being considered. It has been selected as the reference design.

The feasibility assessment report forms a summary of several detailed reports. All relevant detailed reports are referenced.

An analytical and experimental program, described in this report, shows that the proposed design of the TWC can withstand the postulated loads.

A historical account of the prototype container development program, including all analyses and testing is presented in this report.

Several preliminary tests were conducted to evaluate the viability of the concept. The pouring properties of several granular materials (particulates) were evaluated and shown to be satisfactory. Compression tests showed that they had good strength at the hydrostatic pressures anticipated in the repository. Their long-term stability was demonstrated in a set of creep tests, each test being up to 45 days in length. Several other properties of particulates were also evaluated at this stage. These include:

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dust content, moisture content, ease of handling, availability and cost. The mechanical properties of titanium were also examined.

A preliminary stress analysis showed that the container would withstand the postulated loading conditions and develop only small plastic deformations. These deformations are considered to be acceptable.

A container prototype was designed and manufactured to Ontario Hydro specifications. Several manufacturing faults were identified during a preliminary examination. Dimensional and ultrasonic inspection of the container revealed material undercuts during polishing, and uneven weld quality.

Assembly of a full-scale prototype showed that it can be achieved without significant difficulty. The particulate was poured and packed successfully and did not fracture or creep noticably during the hydrostatic tests. Handling of the container posed no difficulties.

The hydrostatic test program was conducted in seven stages including a 16-day test at 10 Mpa pressure and 150°C temperature, and two tests in which quantities of particulate were removed to create artificial voids. As anticipated, small plastic deformations were measured. Localized instabilities were observed following the tests with voids. The container survived all of the tests without loss of integrity. Even a large void of over 1.4 litres did not cause it to fail.

Detailed stress analysis conducted following the hydrostatic test program has demonstrated that numerical techniques can be used to simulate the container behaviour under postulated external loads. The analysis can be used further to investigate the container behaviour in detail and to optimize the container design.

Following the hydrostatic test, the container was cut open. The moisture content inside the container was low. The particulate was undamaged. Detailed examination of the welds showed some defects, although these were small.

Several items still remain to be resolved to fully demonstrate the feasibility of using the container for the disposal of used fuel. These include:

- evaluation of container corrosion
- evaluation of remote handling

- determination of possible handling accidents
- protection of the container in the event of an accident
- review of the economics of the container disposal scenario.

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NOMENCLATURE

AECB	-	Atomic Energy Control Board
AECL	-	Atomic Energy of Canada Limited
Container	-	a receptacle for burying used fuel waste
Disposal Vault	-	a facility used to emplace or discharge waste materials with no intention of retrieval
Disposal System	-	a disposal system and the transportation facilities needed to bring the nuclear fuel wastes from the interim storage sites
Ontario Hydro Container	-	synonymous with Thin-Walled, Particulate-Packed Container
OHRD	-	Ontario Hydro Research Division
Particulate	-	Granular Material such as Glass Beads or Steel Shot
SSC	-	Stressed-Shell Container - A disposal container having a sufficiently thick shell to provide structural reinforcement
TWPP Container	-	Thin-Walled, Particulate-Packed Container
Used fuel	-	Fuel extracted from a reactor at an end of its useful cycle
WNRE	-	Whiteshell Nuclear Research Establismment in Pinawa, Manitoba

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FEASIBILITY ASSESSMENT OF THE PARTICULATE - PACKED, THIN - WALLED CONTAINER

1.0 INTRODUCTION

The responsibility for studying the disposal of used fuel waste from CANDU Nuclear Generating stations lies with the Atomic Energy of Canada Limited (AECL). Under an agreement /1/, Ontario Hydro is providing a Technical Assistance Program (TAP) to AECL in this area. The development program for the Thin-Walled, Particulate-Packed (TWPP) container is being conducted by several departments of Ontario Hydro, as part of this agreement. The TWPP container concept is one of several container designs currently being considered by AECL for the disposal of used fuel.

The TWPP container is being developed for isolation of unreprocessed used-fuel bundles in an up-to 1000-m deep repository. In this concept, the used fuel bundles are placed in a thin steel basket; the basket is then placed in a thin titanium shell and all void space in the container filled with a granular material (particulate). The layout of the assembled container is shown in Figure 1.

The project was divided into several phases:

- evaluation of several particulates and selection of a reference particulate
- container design
- design and construction of prototype container
- prototype test program
- stress analysis
- feasibility assessment.

This report discusses the results of work completed to date,

including a chronological account of all the design processes, tests, analyses and other activities. Many of these activities have been detailed in past reports (References /3/ through /10/).

The program has demonstrated that the Thin-Walled, Particulate-Packed container is a feasible concept. With further refinements, disposal using the TWPP container concept should prove to be both technically sound and economical.

To fully demonstrate the usefulness of this concept, it is still necessary to show that the container:

- can be assembled in a hot-cell environment in a reliable and econimical way; and
- will not be subject to excessive corrosion.

2.0 CONCEPT DEVELOPMENT

Used fuel disposal is postulated to take place in a deep (up to 1000 m) vault/2/. A conceptual vault diagram is illustrated in Figure 2. It shows schematically the above-ground facilities where the site administration would be located, and where fuel bundles will be transferred from the shipping casks to the immobilization containers. Several shafts will provide access to the vault. The vault will consist of corridors and rooms. The containers will likely be placed vertically in boreholes drilled in the vault floor.

The TWPP container concept was originally proposed by the Whiteshell Nuclear Research Establishment (WNRE). It was suggested as an alternative to a thicker shell, self-supporting container called the Stressed-Shell Container (SSC).

The TWPP design has a thin outer shell supported by a granular material (particulate). The container dimensions were chosen to accomodate 72 bundles. The outer shell would be made of a corrosion-resistant metal such as Grade 2 titanium. The shell thickness was based on a requirement that the container should survive 500 years without perforation by corrosion.

A test program was conducted to determine if granular materials could be packed adequately and provide adequate strength to support the container shell under an external pressure of up to 10 Mpa (1470 psi), which could exist in a fully flooded vault.

3.0 CONTAINER DESIGN

3.1 Design Criteria

The container is designed to meet the following loading conditions:

- An external hydrostatic pressure of 10 Mpa (1450 psi) which could exist in a flooded repository
- A maximum temperature of 150°C
- An internal pressure due to the increase in the internal temperature by 130°C, assuming no external pressure.
- Total container weight during lifting.
- Dynamic loads due to vibratory compaction and handling.

The top lid weld must be suitably designed for remote assembly and inspection.

There are no design codes or standards directly applicable to disposal containers that would provide guidelines for performance limits. Where possible, the ASME Boiler and Pressure Vessel Code, Section III was used. In cases where this code could not be used, factor of safety of two on ultimate strength is used.

3.2 Design Philosophy

The titanium shell is designed to be supported by a carefully packed particulate. The stiffness of a particulate in a free state is much lower than the modulus of elasticity of titanium, but increases rapidly with rising external pressure. Thus, some compressive, plastic deformation of the titanium shell is anticipated. Such deformation should not jeopardize the integrity of the container. However, poorly packed particulate or excessive gaps between the top surface of the particulate and the top lid could result in large voids and in failure of the container's integrity.

3.3 Design Description

The TWPP container consists of a mild steel basket assembly that rests inside a cylindrical titanium shell. The basket has a capacity of 72 fuel bundles. Empty space inside the container is filled with a granular material compacted by vibration to form the structural matrix. The container is about 2246 mm high and has a diameter of about 633 mm (see Figure 1).

The outer shell is made of rolled ASTM B 265 grade 2 titanium plate, 4.76 mm thick. The prefabricated titanium shell should be heat treated after welding to improve uniformity of the cristallograthic structure and shell ductility. Heat tratment is not mandatory, according to Section VIII of the ASME Pressure Vessel Code. The Code recommends the use of temperatures of 538°C to 593°C for unalloyed titanium, for post weld heat treatment.

The fuel basket assembly provides means of loading fuel bundles. It holds the bundles in place while allowing free particulate flow. It also reduces the chance of bundle damage during handling and particulate packing.

The basket consists of nineteen 4-in sch. 10 tubes concentrically arranged, as illustrated in Figure 3. The central pipe is surrounded by an inner ring of six, and an outer ring of twelve pipes. The outer diameter is 556 mm. Each pipe (except the centre pipe) can contain four bundles. The centre pipe is used for handling only.

A spoked wheel arrangement (see Figure 4) at the bottom of the basket is used to support the bundles inside the pipes. It consists of eleven 19-mm by 38-mm steel bars, fillet welded to a NPS 24-in pipe ring. This ring transfers the weight of the basket with bundles to the outer perimeter of the container's bottom lid. The ring also adds rigidity to the titanium shell in the weld area at the bottom lid by reducing deformations in the bottom lid to shell junction. A spacer ring is located at the top of the basket. It is constructed of a 50 mm-long segment of NPS 24 in steel pipe, as shown in Figure 5. The spacer ring positions the basket in the outer shell and transfers the dynamics loads from the basket to the outer shell during vibratory compaction. Because the fuel basket has no special performance requirements beyond supporting the fuel, it can be made of mild steel.

A 6.35-mm thick bottom head is GTA welded to the shell. The top lid is 4.76 mm thick and will be resistance-diffusion bonded to the shell after assembly. A larger thickness is required for the bottom plate to support the weight of the particulate and the basket during lifting.

A lifting ring is provided at the top of the cylindrical shell, above the top lid (see Figure 6). In this arrangement, there are no lifting loads on the top plate.

The design of the prototype container is described in Reference 3 in more detail.

4.0 EVALUATION OF PARTICULATE

4.1 Introduction

The container integrity largely depends on the mechanical properties of particulate, its long term stability and its effect on the shell material (titanium). Several tests were performed to determine the mechanical properties of various particulates and titanium in preparation for the prototype design. These preliminary tests have shown good fluidity and strength for most of the tested particulates. Twelve particulates were tested:

- Wedron sand type 4098
- Glass beads 0.6-0.9 mm
- Glass beads 1.0-1.2 mm
- Glass beads 1.4-1.68 mm
- Steel shots 0.6-1.0 mm
- Bauxite grains size up to 1 mm.
- Interprop (bauxite with 15% silicon)
- Sintered bauxite
- Zircox 51702
- Combination of 38% rutile, 38% zircon, 24% garnet (R-Z-G)
- Zircon
- Rutile

The selection of particulate for the prototype test program was based on three tests:

a) A vibratory compaction test, in which particulate packing characteristics and dust content were determined.

b) An axial compression test to determine strength, modulus of elasticity, Poisson's ratio and bulk modulus.

c) A creep test to determine structural stability of particulate.

The criteria for selection of particulate for the prototype were:

a) good vibratory packing characteristics
b) low dust content
c) strength - no breakage below 20 MPa (2900 psi) pressure
d) high bulk modulus of elasticity
e) good chemical stability, and
f) low creep induced deformation.

The required strength of particulate is based on the maximum postulated pressure in the vault with a factor of safety of 2, at temperatures of up to 150°C.

Glass beads were recommended as the reference particulate and for packing of the prototype container because they are dust free, have adequate strength, good packing characteristics, good stability and allow for good control of chemical content.

For used fuel disposal, other criteria for evaluation of particulates must be considered. The selected particulate might also be able to offer:

- Chemical and radiation stability
- Good heat transfer and low thermal expansion
- No swelling when wet
- The ability to limit water access if the container is penetrated
- Retention of radionuclides
- Low cost and good availibility.

The results of the particulate test program were presented in References 4 and 9 in significant detail. A brief discussion of the program is presented below.

4.2 Packing of Particulate

4.2.1 Procedure

The fuel bundles in the basket tubes will resist the flow of particulate. Different accelerations, frequencies and amplitudes were used to evaluate how much the bundles resist the flow of particulate and to determine the optimal packing conditions.

A plexiglass tube 1092 mm long and 113 mm inside diameter was used to test the particulate packing properties. Two simulated Bruce bundles containing 36 elements (see Figure 7) were inserted into the tube. The tube was mounted on a shaker table, as shown in Figure 8. While the system was stationary, particulate was poured into the tube until it covered the bundles, shown in Figure 8b. The bundles did not offer significant resistance to the flow of the particulate. To further improve packing density, sine wave vibration was applied at several frequencies and accelerations for five-minute periods.

Following particulate pouring, and each stage of vibratory compaction, a visual inspection was made for localized voids. The release of dust was observed during pouring of particulates into the tubes.

4.2.2 Results

The dust content of particulates varied widely. Steel shot and medium and coarse glass beads produced almost no dust. The dust

content of all particulates is given in Table I by ranking from 0 (no dust) to 5 (dust inhibits testing).

The weight and volume of particulate were measured before and after each section of a test. The calculated densities were compared in Table I with a "reference density" equal to the density of a matrix having a face-centred-cubic configuration of uniform spheres. The reference density is equal to about 74% of the density of a solid block of material of which a particulate was made.

The bundles provided little resistance to the flow of particulate. The annular space between a bundle and a tube was not required for compaction. Most of particulates poured well without any voids. The "as poured" packing had a density of 80% to 90% of reference density. Only Zircox 51702 formed large voids. The large variation in the grain size of the fine glass resulted in better packing density. However, significant separation of various sizes was also observed. Particulate settling following vibratory compaction can be seen in Figure 8c where part of a fuel bundle is exposed.

Following vibratory compaction, the top surface of the particulate was observed to be inclined at an angle of up to 30°, in several tests. This was most pronounced in sand. This behaviour was not significant during the prototype program and could be characteristic of small-diameter containers. Also, particulate with a smooth surface (such as glass beads) form smaller slope.

An increase in the frequency from 25 Hz to 90 Hz improved the packing significantly. The improvement was small as frequency was increased further to 180 Hz. Packing improves with the increased acceleration. Vibratory compaction should be only in horizontal direction and continue for at least five minutes.

4.3 Strength of Particulate

4.3.1 Procedure

Tests were conducted, using equipment shown in Figure 9, to determine the mechanical properties of particulates, such as:

- strength to break-down
- Poisson's ratio
- Bulk modulus
- shear modulus of elasticity
- Young's modulus of elasticity

A method of deriving the values of these parameters is discussed in Reference 10.

The cylinder was open at both ends and was supported on a flexible rubber pad. The particulate was compressed between two pistons to minimize the pressure gradient in the cylinder due to arching. The arching effect causes an axial pressure drop in the particulate by transferring the load onto the cylinder/4/.

The cylinder in Figure 10 was used to evaluate the effect of a fuel bundle on particulate stiffness.

4.3.2 Results

The calculated values of Poisson's ratio, modulus of elasticity and bulk modulus for all particulates are listed in Table II. Steel shot was the stiffest particulate tested. However, its Young's modulus is 150 times lower than that of solid steel. The crushed bauxite, Zircox 51702 and R-Z-G combination are the softest particulates. The ratios of the particulate to titanium moduli are shown in Table II, column Ep/Et. The Young's modulus of the particulate is not constant. Calculations of the moduli at several different pressures indicate that they increase with pressure, according to the formula $Ep = (pE^2)^{0.33}$, where p is the pressure and E is the Young's modulus of a corresponding solid material. The above formula assumes that the Poisson's ratio is constant (see Reference/8/).

The values listed in Table II were derived from data measured at pressures close to the maximum postulated vault pressure.

If a bundle is present in a volume of particulate, it will significantly increase (up to 7 times) the apparent stiffness of the system, as shown in Table II.

Most of the particulates have an acceptable strength (except crushed bauxite, zircox 51702 and R-Z-G). Glass beads appear to be the weakest because of their clear particle fracture point at pressures above 27 MPa, as shown in Figure 11c.

Compression tests were also conducted at elevated temperatures (160° to 200°C). A comparison of results obtained in the ambient and elevated temperature tests is shown in Figure 11. This figure shows the consistancy of results obtained at both test temperatures for three particulates, at pressures of up to 30 Mpa or until initial cracking of the particulate occurred. Following initial cracking, many particulates appear to be stronger at elevated temperature due to reduced brittleness. The properties of particulate within the elastic range are shown in Table II and are nearly identical for both ambient and elevated temperatures.

The results obtained in our tests agree with values and observations given by Lambe and Whitman in Reference 14.

The mechanical properties determined from the test program are approximate due to the limited capabilities of the testing facilities. For some particulates, the differences between the obtained properties could be within the test error.

4.4 Creep of Particulate

4.4.1 Procedure

Materials such as glass beads were suspected of having slow, plastic deformation (creep) and possible sintering (due to high stress) in the vault environment. Considering an inevitable void ratio of about 26% in all granular materials of uniform size, such plastic flow could lead to large volume reductions.

All particulates evaluated during the compaction tests were tested for creep at 150°C and at pressure of 10 Mpa, using the equipment in Figure 12.

Particulate samples were poured into the tubes and compacted by striking the outside of the tubes with a rubber mallet. Packing was inconsistant which resulted in the significant settlement in the early stages of the test. The longest test lasted 45 days. In addition to the steady state creep tests, the behaviour of the particulate under pressure and temperature cycling was evaluated.

4.4.2 Results

The results of the tests are presented as graphs of strain as a function of time or number of cycles. The settlement of particulate follows a logarithmic curve in most cases. The initial settlement seen in Figure 13 is due to the incomplete packing during the preparation for the test. Including this initial packing, the total 500-year settlement is expected to be within 0.05%, for most particulates. Glass beads are the reference particulate. Their test program was extended to evaluate their stability in distilled, de-ionized water and in Standard Canadian Shield Saline Solution under full pressure and temperatures up to 75°C (see Figure 14). Good consistency in results was obtained for all tests of glass beads - their behaviour is not affected by the presence of the liquids.

Although the reliability of extrapolating a 41-day test for an extended period of time is difficult, it indicates a settlement of less than 0.005% after 500 years, for most particulates (see Figure 13). This extrapolation was made using equations:

$$e = A \ln(Bt) \quad \text{or} \quad e = A \ln(Bn)$$

where

e - strain
A and B - equation constants
t - time in hours
n - number of cycles

Values of the constants for various particulates are shown in Table III.

Pressure cycling (see Figure 15) produces larger settlement than steady state loading. For example, steady-state testing of glass for 1000 hr at 150°C produced a settlement equal to that obtained after only two pressurization cycles from 0 to 10 Mpa. Temperature cycling has a similar effect on settlement. Although the graphs follow the standard creep pattern, the existence of a creep mechanism could not be confirmed in any of our tests. Only steel shot showed a constant rate of settlement indicating a possible creep (see Figure 13d). The observed settlement is assumed to result from reorganization of the grains of particulate, rather than from creep itself.

4.5 Summary of Results

Of the twelve tested particulates, only three are considered viable: glass beads, Interprop and sintered bauxite. All others were disqualified during the compression test, except steel shot and sand. Zircox 51702 was considered unsuitable in all tests (large voids were obtained in packing test, Young's modulus is too low and creep strain is high). Excessive dust was observed in R-Z-G combination, sand, zircon, zircox and rutile. Steel shot was disqualified because of the possible mechanical interaction with titanium (steel shot is hard and could introduce high Hertz's stresses in titanium. Steel shot was also found to creep. Glass beads are considered the most suitable particulate because of good control of their chemical composition, low dust content, good packing and adequate modulus of elasticity.

The obtained properties of particulate are only approximate. Further testing is required to better understand their behaviour at the high pressures of up to 10 MPa. Creep tests were largely inconclusive.

5.0 BUILDING OF PROTOTYPE

When the project was undertaken, it aimed at demonstrating the feasibility of using the TWPP container concept for disposal of used fuel, in a comprehensive test program, including hydrostatic testing.

A single, full scale prototype container was built. The outer shell was made of the reference material - ASTM SB-265 Grade 2 titanium to facilitate good interpretation of results. The cylindrical shell and the top plate were made of 4.76 mm thick plate, while the bottom plate was 6.35 mm thick.

The basket assembly was constructed of mild steel. All pipes were ASTM SA-53 Grade B steel. The spoke wheel was made of SA-36 steel.

The 620 mm inside diameter prototype was about 2.3 m high and consisted of a cylindrical section welded to the bottom plate. The container prototype is shown in Figure 16. The top plate was supplied as a separate component (see Figure 17). Lifting was through three reinforced holes spaced 120° apart, near the top of the container.

The outer shell was fabricated from two rolled plates welded together, using the GTA welding process. The bottom and top heads were formed by spinning.

A more detailed description of the protopype is presented in References 3 and 8.

To provide the container with similar strength to that expected in an actual disposal container, 48 simulated fuel bundles were prepared. These simplified bundles were expected to provide an additional strength to the outer ring of the basket tubes (see Figure 3). They also provided larger resistance to particulate flow than the actual bundles would. The conservative estimate of particulate packing performance was obtained from the test program. A steel, simulated bundle is shown in Figure 7. Glass beads sieve -18 to +25 or 0.71 mm to 1.00 mm diameter were used in the prototype.

6.0 PROTOTYPE INSPECTON

The container was made of two rolled 4.76 mm-tick plates welded together. All welds were brushed by the manufacturer. The mid-height, circumferential weld (in Figure 18) was polished and undercut to a thickness of less than 4.76 mm. Because of this, we were not able to fully determine through non-destructive examination what welding quality was achieved. The welds were evaluated in detail following the hydrostatic test program, and were found to be better than initially anticipated, see Section 11.2.

Dimensional examination revealed out of roundness of at the top of the container, and outward sloped sides on the top lid.

7.0 PROTOTYPE ASSEMBLY

7.1 Shaker Table

A special shaker table (in Figure 19) was constructed with the actuator attached near the container's centre of gravity. The actuator was attached to the movable part of the shaker table which consisted of a frame of large steel beams ("shipping frame"), enclosing the container. The compaction was achieved using sine wave excitation at accelerations of up to 4 g peak-to-peak in the horizontal direction only. Vertical excitations were not used because of the possibility of particulate flowing under the internal basket and floating it upward, if accelerations exceeded 1 g.

7.2 Particulate-Packing of Container

Initially 635 kg (1400 lbs) of particulate were used to fill the container. An additional 68kg (150 lbs) of particulate were added as the particulate settled, to retain the level of particulate at 20 to 25 mm above the basket. The packing took eight steps, see Table V. A brief evaluation of packing was conducted at various frequencies and accelerations. The best packing was achieved at 40 Hz and the highest acceleration tested (4 g). The packing of particulate was discussed in detail in Reference 8.

The container was instrumented with strain gauges prior to packing. The largest stress measured was 11 MPa (1,600 psi). During insertion of the lid, an additional stress of 64 MPa was measured. The total stress generated during assembly did not exceed 30% of yield.

7.3 Container Closure

Although the container closure lid was designed to fit with relative ease, the out-of-roundness of the container shell plus the slope on the lid required a considerable force to insert the lid. A final vibratory compaction was made with the lid in place. Force was again used to press the lid down and eliminate the 3.5 mm gap that formed after the last compaction.

The lid was held in place by a special jig during handling and shipping from the Ontario Hydro laboratories (located in Toronto, Ontario) to WNRE (in Whiteshell, Manitoba). Vibrations during transportation seem to have created a void under the top lid of up to 14.5 mm high (4.38 litres volume). The exact size of this void is not known. Its size was estimated during the post hydro-static test inspection when the distance between the top lid and

the basket was found to be smaller by 14.5 mm than we expected from measurements taken during the packing test. The effect of this void on tests and analysis is discussed further in Sections 9.0 and 12.0.

The closure weld was made at WNRE. Although the weld showed some discoloration and unevenness, it performed well during all tests.

8.0 CONTAINER INSTRUMENTATION

The prototype container was extensively instrumented with both bondable and weldable (Ailtech type) strain-gauges. Three thermocouples were used at different elevations to monitor temperatures on the container surface.

Because of the harsh environment in which the strain gauges were required to operate, strain-gauge development programs were undertaken by both Ontario Hydro /12/ and WNRE /13/. The strain-gauge mounting methods proposed involved multiple encapsulations, including spot-welded metal caps. The Ontario Hydro method is shown in Figure 20. The locations of the strain-gauges are shown in Figure 21. Several additional weldable, Ailtech type gauges were installed for the two tests with artificial voids. The locations of the gauges used during these tests are shown in Figure 22.

9.0 HYDROSTATIC TEST PROGRAM

Since only one prototype test was planned, an extensive set of test runs was established. The hydrostatic tests formed the main part of the tests, and consisted of seven stages:

Stage 1 - preliminary tests, ambient temperature of 20°C, up to 1 MPa pressure
Stage 2 - initial test at 100°C and 10 MPa pressure
Stage 3 - second test at 125°C and 10 MPa
Stage 4 - full temperature test at 150°C and 10 Mpa
Stage 5 - 16-day, long term test at 150°C and 10 MPa
Stage 6 - centre void test at 150°C and 10 MPa
Stage 7 - side void test at 150°C and 10 MPa

The test results are presented in graphical form showing strain (or displacement) as a function of pressure. Curve smoothing techniques were not used.

The bondable gauges performed well during preliminary tests at pressures of up to 10 MPa and at temperatures of 100°C and 125°C. A large amount of data was collected during these tests.

During the 10 Mpa, 150°C test, most of the bondable gauges failed and only data from the weldable gauges were available. The results of the tests are expected to have some error, because the drifting of the zero reading is always present in gauges. This drifting is amplified by the adverse test conditions such as high strains and high temperatures.

9.1 Test Facilities

The Whiteshell Nuclear Research Establishment built a large pressure vessel for hydrostatic testing of prototype containers (see Figure 23). After the prototype container was placed inside the vessel, the vessel was filled with chemically treated water. A small gap was left at the top for pressurization. The vessel was pressurized using nitrogen. Electronic data logging was used to monitor the instrumentation.

9.2 Preliminary Tests

If the outer shell had not been supported, it would buckle at pressures as low as 0.25 MPa. Several low-pressure cycles at 20°C were conducted to determine if significant buckling would occur. The top lid was the only area where noticable plastic deformation occurred. Large strains resulted from a deformation of the top lid by up to 14.5 mm to close the gap, mentioned in Section 7.3.

9.3 First-Stage Test

The first test was conducted at 100°C and a maximum pressure of 10 MPa. The test was completed successfully. A large volume of strain and temperature measurements was obtained.

During the first 10 MPa test, the plastic deformation continued. A permanent strain of 0.005% was recorded at the rim of the top lid. Large deformations occured in the top lid, although strains measured at the gauge locations were low. The top lid is believed to have settled down from about 22 mm above the basket to about 7.5 mm, as illustrated in Figure 24.

Strain and deformation in the cylindrical shell depend on the proximity of discontinuities such as the top and bottom lids or the circumferential weld. Four different elevations were monitored. Strains measured just below the top lid during pressurization are shown in Figure 25. The plot shows the wide variation of strains around the container circumference. The average hoop strain of -0.33% is about twice the axial strain, which averages -0.18% The circumferential variation in results has not been explained fully. It is possibly due to geometrical discontinuities (out-of-roundness, thickness variations, etc) and metallurgical discontinuities (such as welds).

Gauges located 750 mm below the top of the cylindrical shell are sufficiently far from most discontinuities that these effects are negligable. Figure 26 shows strains at that location. The hoop strains are compressive at about -0.2%. The hoop strain near the axial weld (solid line on the plot) is the highest at -0.23%, apperently due to the discontinuity. Axial strain is near zero. The axial force on the container is supported by the basket and particulate. Only a small, positive strain was measured, due to the Poisson's effects.

Total compressive strains in the hoop direction measured near the bottom plate were less than 0.2%. The axial deformation is produced by Poisson's effects only.

9.4 Second Stage Test

For the second stage test, the container was heated to 125°C. Readings were taken during pressurization in the steps of 0.5 MPa from 0 to 9.5 MPa. Strain measurements during depressurization are not available because of a seal failure in the test chamber. Strains measured during the pressurization were generally lower than strains obtained during the first stage test. Figure 27 shows the comparison of strains on the cylindrical shell.

Strains in the top lid away from rim are low and do not change significantly between tests. This is attributed to the nearly parallel settlement of the top plate, as shown in Figure 24.

9.5 Third Stage Test

The third stage test was conducted at 150°C. A full pressure of 10 MPa was applied. Good strain and temperature measurements were obtained during pressurization and depressurization. Plastic deformation was not seen during this stage, as illustrated in Figure 28.

9.6 Long-Term Test

The fourth pressure cycle was intended to show the long-term stability of the container. The pressure vessel was heated to 150°C and pressurized to 10 MPa. The pressure and temperature were maintained for 16 days. An examination of the container following the test did not reveal any significant additional plastic deformation. In most locations monitored, the strains were purely elastic. Typical plots of strain versus external pressure and time are shown in Figure 29. In the cylindrical shell, the pressurization and depressurization curves are similar. The time dependent curve (Figure 29b) shows no increase in strain with time.

9.7 Centre Void Test

A 0.21 L void was introduced under the center of the top lid to assess the effect of imperfect packing. The void was about 10 mm deep and had a 125 mm diameter. During the subsequent 10 MPa, 150°C test, a localized dent formed in the top lid. The diameter of the dent was about 250 mm. Depth of the dent was up to 6 mm. The deformation around the void is shown in Figure 30.

Several additional strain-gauges were installed near the void to monitor strains in the area, as shown in Figure 22. The strains at the void were significantly larger during this test than during the previous 150°C tests, as shown in Figure 31. Away from the void, the strain difference disappears (see Figure 31b).

9.8 Side Void Test

A second void was introduced below the top lid, near the cylindrical shell, see Figure 32. A significantly larger volume of glass beads was removed for this test: 1.64kg (0.80 L). The hydrostatic test was repeated at 10 MPa and 150°C. The test produced large but localized deformations. A large dent formed in the lid as shown in Figure 33. Figure 34 shows two buckling waves in the cylindrical shell.

Large, non-linear strains were measured near the void. Away from the void, the strain patterns were close to the results of the previous tests, when the void was absent (see Figure 35).

The container retained its integrity although large plastic deformations occured. The plastic deformations at the top lid resulted from closing of several large voids. During the preliminary tests, a void of 4.38 litres is believed to have been closed. The total size of all voids is estimated to be:

$$\text{Void} = 4.38 + 0.21 + 0.80 = 5.39 \text{ litres}$$

10.0 HANDLING TESTS

Following the hydrostatic tests, the prototype container was provided with more gauges, and lifted to determine the stress levels during handling. Four three-gauge rosettes and two double gauges were used, as shown in Figure 36. This test showed that stresses in the container during lifting were low. The largest stress measured during the handling test was less than 21 MPa. This bending stress occurred in the bottom lid. The allowable stresses, according to the ASME Boiler and Pressure Vessel Code, is 200 MPa. A more detailed stress distribution in the

titanium shell is presented in Figure 36.

11.0 POST HYDROSTATIC TEST INSPECTION

11.1 Evaluation of Particulate

In preparation for the detailed examination of the container, the container was opened. Before the container was emptied, the particulate at the top surface was carefully examined. The main observations were:

- Only few grains of particulate were broken.
- The particulate contained some moisture when it was packed. A thin layer (less than 20 mm) of slightly moist particulate was found near the top of the container.

11.2 Evaluation of Titanium

The container was ultrasonically examined during the preliminary evaluation of the prototype, prior to the hydrostatic tests/16, 17/. The original inspection indicated that the welds contained inclusions. A destructive examination reaffirmed only some of the flaws detected in the original examination, before the hydrostatic tests/17/.

Tensile tests were performed on titanium samples obtained from the top part of the prototype container. Both the parent metal and the axial weld were tested. The parent metal was found to have a lower modulus of elasticity and yield strength than required by the ASTM standard B 265 Grade 2, although its chemical composition met the requirements. The results of tests performed on the shell material are listed in Table V.

The plate material was very ductile. In the specimen made from the weld material, cracks started forming during shear tests at about 90% ultimate strength, which would suggest some brittleness.

Several hardness tests were performed on a specimen containing the weld. The Rockwell B procedure was used. The tests indicated that the weld area was the softest with readings around B 75. The weld transition zone was the hardest at B 89. The hardness of the parent metal was about B 87. The low hardness of the weld material was attributed to the large grains present in this area. The high hardness is assumed to be caused by dissolved oxygen and nitrogen. The metallogrophic structure of the weld and parent metal areas is shown in Figure 37.

After the container was opened, its top section containing the

lid and top 300 mm of the cylindrical shell was sent for weld examination. Both the longitudional seam weld and the top lid closure weld were examined. The longitudinal weld was made by the submerged arc welding process. The use of this process resulted in formation of large, serrated alpha grains containing mechanical twinning in the heat affected zone/12/. The grains of the parent metal were fine and did not contain twinning. Twinning and large grains resulted in reduced ductility of the weld material to 17%, below the ASTM required value of 20%. The results of the examination are discussed in detail in Reference 17.

Forming of the lid resulted in a harder and less ductile metallic structure than anticipated. The top lid should be annealed after forming. Submerged arc welding should not be used for fabrication of the titanium containers for disposal of used fuel.

12.0 STRESS ANALYSIS

12.1 Introduction

An extensive stress analysis program was conducted to show that we can simulate the results of the hydrostatic test program using the finite element techniques. The finite element analysis will then be extended to evaluate the behaviour of the container under several conditions, such as:

- the behaviour of the bottom plate which could not be evaluated during the test program
- the internal pressure due to the increase in the inside temperature from 20°C during assembly to 150°C in the vault
- the effect of localized or gross corrosion which would reduce the thickness of the container below the postulated 4.76 mm
- the formation of an uniform void caused by a long term settlement of particulate.

Most of the above conditions are still being analysed and are not included in this report. A separate report will be issued describing the results of all analyses/10/.

Properties assigned to the modelled container components are based on the results of previous studies and on the ASTM specifications. Properties of particulate were described in section 3.0 (E_p = 337 MPa, ν = 0.41). A long term settlement of particulate is expected to produce a strain of 0.000247 after 500 years. Steel basket tubes are assumed to have standard steel properties (E =200,000 MPa, ν = 0.3). The titanium shell was found to be

highly stressed in some locations. Elastic-plastic properties were used in some analysis as follow:

Elastic Young's modulus	E = 100,000 MPa
Elastic Poisson's modulus	ν = 0.41
Yield strength	Sy = 216 MPa
Strain hardening modulus	Eh = 6,000 MPa
Strain at the end of strain hardening zone	e = 2.0%
Maximum strain	e = 20%
Ultimate Strength	Su = 345 MPa
Modulus of elasticity in plastic zone	Ep = 125 MPa

An experimentally determined stress-strain curve for titanium used to make the prototype is compared with the values used in analysis in Figure 38.

A more detailed description of the analysis can be found in Reference 10.

12.2 Comparison with Tests

Many assumptions were made during the finite-element modelling. For example, the particulate was assumed to be a solid material with a tensile and compressive moduli of elasticity. The results of the hydrostatic test program are used here to validate the finite element models and to show that the assumptions introduce a small error. Also, only a limited volume of experimental results is available (at strain gauge locations) for comparison, it shows that good correspondence between results of tests and analysis was obtained.

The effect of the external pressure of 10 MPa was evaluated in three stages. Initially the container was assumed not to be axisymmetric because of the internal basket. The behaviour of the cylindrical shell, away from discontinuities, was considered using a pie-shaped model and cyclic symmetry of the basket (see Figure 39). This model allows us to evaluate if the non-axisymmetric internal structure of the container (formed by the basket) is significant. After showing that the titanium shell is axisymmetric (within a small error), the rest of the analysis considered the container to be axisymmetric. Perfect packing was assumed in the model of the entire container. The results of this analysis were compared with results of the second-stage (125°C) hydrostatic test. A separate model was analysed to compare the results of tests and analysis of the 14.5 mm settlement at the top.

The pie-shaped model is shown in Figure 39. All components of the container are explicitly modelled, except for the bundle-particulate combination which is modelled as a uniform isotropic

structure. Several runs using several different stiffnesses of the bundle-particulate combination showed that the results are insensative to this property over a large range of stiffnesses.

The analysis showed that the deformations in the titanium shell are not fully axisymmetric, because the basket is not axisymmetric. The average deformation of the titanium shell is 0.544 mm (0.57 mm was measured during tests). This deformation varies by up to 5% depending on the location relative to the basket tubes (see Table VI). This 5% variation is small, allowing us to analyze the titanium shell as an axisymmetric structure. The hoop stress in the shell exceeds yield slightly, at -217 MPa. The stresses in the steel basket are below 55% yield. The highest compressive stress in particulate is -8 MPa.

The analyses were repeated for several pressures and by adjusting the stiffness of the particulate for each pressure according to the formula $Ep = (pE^2)^{0.33}$, see Section 4.3.2. The comparison of the measured and calculated hoop strain during pressurization is shown in Figure 40. The good correlation between the two results shows that finite element analysis can be used to approximate the test results.

The stress distribution inside the container is non-axisymmetric. Axisymmetric analysis is only used to evaluate stresses and deformations in the titanium shell.

The axisymmetric analysis of the entire container assumes no voids and the container is assumed to behave elastically. The model, shown in Figures 41 and 42, contains several simplifications. The titanium shell is modelled by shell elements 4.76 mm thick. The particulate between the shell and the basket is modelled as a uniform ring with a constant thickness of 40 mm. The layer of particulate above the basket is also assumed to be 40 mm thick. The steel lifting plate, covering the centre tube is included in the model. The basket and its contents were modelled as a uniform axisymmetric structure with isotropic properties. Its modulus of elasticity was assumed to be 2800 MPa and Poisson's ratio was 0.3. The bottom ring and spoked wheel were modelled as a solid steel plate.

The results of this analysis resemble the results from the 125 C hydrostatic test, in which most deformations were elastic. Table VII compares strains measured during the test with those calculated in the analysis. This comparison further confirms that the finite element analysis can be used to successfully predict the container's behaviour. However, the calculated axial deformation at the top lid was small (2.7 mm). To better model the large deformations detected in the prototype test program, a partial model containing gap elements was created.

The model in Figure 43 has a 20-mm thick layer of particulate. Above the particulate, a 14.5-mm gap was modelled. To allow for the large deformations, titanium was represented as an elastic-plastic material described in Subsection 12.1. Throughout the model, stresses in the titanium shell exceeded yield significantly. We know that titanium has a large plastic zone allowing strains of up to 10% without failure. The failure criterion of the container shell will be based on the largest local strain.

The analysis has shown that the top plate should have deformed until it was in contact with the particulate at pressures below 1 MPa (see Figure 44). This pressure was used during the preliminary tests, which explains the large strains detected during those tests. As the pressure was increased to 10 MPa, only small additional plastic strain occurred. Both the 100°C test and the analysis support this interpretation.

A direct comparison of strains in the lid area is difficult because the strains vary widely with radius and the location of the strain gauges is known only approximately. Since strain gauges tend to integrate strain over their length, it is possible to find an area of the lid where measured strains would agree with the measured results, as shown in Figure 45.

The finite element method has been shown to be an adequate tool to analyse the container. The analysis will be extended for other cases, not included in the test program.

12.3 Internal Pressure

An increase in the container temperature from 20°C during assembly to 150°C expected in the vault will increase the internal pressure in the container by 0.0444 MPa. The column of particulate will increase this pressure to 0.665 Mpa at the bottom. If the external pressure is zero, the titanium shell will be in tension. The particulate will not support the shell in this case and it is neglected in the model, shown in Figure 46. The bottom plate is assumed to sit on a uniform and flat surface, maintaining the plate flat.

The internal pressure is low. The resulting stresses are below 70% of the allowables of the ASME Boiler and Pressure Vessel Code, Section III.

13.0 CONCLUSIONS

An extensive program has been conducted to demonstrate that the Thin-Walled, Particulate-Packed container design presents a

viable concept for the disposal of used fuel from the Canadian nuclear power stations. In the preliminary test program, the properties of the internal structural matrix (a particulate material) of the container were evaluated. The particulate was shown to have adequate strength and stiffness to support the thin titanium shell. During 500 years (the postulated container life), well-compacted particulate is not expected to settle significantly. The good performance of the container was demonstrated in a multi-state hydrostatic test program. This program showed that even if there are large voids (of up to 5.39 litres) in the particulate, the container shell has adequate ductility to maintain container integrity.

An extensive stress analyses program is currently underway. It shows that the analysis can reasonably approximate the test results which provides better confidence in the analysis of conditions that were not tested. The analyses confirm the good performance of the proposed design. The analyses are continuing to provide a better understanding of the container behaviour under the complex loading conditions and possible undetected manufacturing errors.

The concept represents a good choice for the reference container.

14.0 RECOMMENDATIONS

The container concept has been shown to be structurally vaiable. Much work still remains to consider many aspects of the container performance including:

- a better understanding of particulate behaviour at high pressures including its creep and settlement mechanisms
- the consideration of various accidental loading conditions
- the refinement of the design to improve the stress distribution
- the refinement of the design to improve the manufacturing and handling conditions
- corrosion of the titanium shell should be evaluated considering the effects of plastic tensile strains in the top and bottom lids.

It is recommended that development of the container should continue to its full demonstration, as the reference container.

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REFERENCES

1. Joint Statement by Minister of Energy, Mines and Resources Canada and Ontario Energy Minister, June 5, 1978.

2. Acres Consulting Services Limited Report, "A Disposal Centre for Irradiated Fuel: Conceptual Design Study", Issued by AECL as a report No. AECL-6415, dated September, 1980.

3. R. Hoy, M. Mikasinovic, "Particulate-Packed, Thin-Wall Container - Prototype Design", Internal Ontario Hydro Report, dated June 9, 1981.

4. B. Teper, "Particulate Compaction Tests for a Particulate-Packed, Thin-Wall Container for Irradiated Fuel Disposal", AECL Report TR-131, December, 1980.

5. Tender documentation for Purchase of the Thin-Wall, Particulate-Packed Container)821 TW 70300 27, dated July 31, 1981.

6. B. Teper, "Preliminary Evaluation of Stress-Strain Distribution in Particulate-Packed Container", Ontario Hydro Research Division Report 81-316-K, October 29, 1981.

7. B. Teper, "Evaluation of the Particulate-Packed, Thin-Wall Container for Disposal of Irradiated Fuel Bundles", CNS International Conference on Radioactive Waste Management, Winnipeg, Manitoba, Canada, September, 12-15, 1982.

8. B Teper, "Test Program of the Prototype of the TWPP Container, Part 1 - Hydrostatic Tests", Ontario Hydro Research Division Report 84-293-K, December 21, 1984.

9. B. Teper, "Test Program of Granular Materials for the Thin-Walled, Particulate-Packed Container", Ontario Hydro Research Division Report 87-154-K, August 27, 1987.

10. B. Teper, "Test Program of the Prototype of the TWPP Container, Part 3 - Detailed Stress Analysis, Initial Results", Ontario Hydro Research Division Report 87-296-K.

11. K. Nuttall, "Container Development and Materials Evaluation", Proceedings of 16-th Nuclear Fuel Waste Management Information Meeting, 1983, AECL Technical Report TR-218.

12. J. Russell, "Protection of Bondable Strain Gauges Under Severe Conditions (10 MPa Water 150 C) Using Sealed Cap Method", Ontario Hydro Research Division Report 83-481-K, December 23, 1983.

13. L.J. Hosaluk, "Developmental Testing of strain Gauge Systems for Hydrostatic Testing of Prototype Fuel Isolation Containers", Atomic Energy of Canada Limited Report TR-283, Dated September 1984.

14. Soil Mechanics, T. W. Lambe and R. V. Whitman, John Wiley and Sons inc, 1969.

15. Memorandum from M.D.C. Moles to B. Teper, dated July 13, 1984.

16. M.D.C. Moles, Ontario Hydro Research Division Report 83-22-H, February 9, 1983.

17. P.Y.Y. Maak, "Evaluation of Fusion Welds in a Prototype Thin-Walled, Irradiated Fuel Container", Ontario Hydro Research Division Report M84-175-K, March 19, 1985.

TABLE I
VIBRATORY COMPACTION TEST RESULTS

TEST NO.	TYPE OF PARTICULATE	AMOUNT POURED (kg)	VOLUME POURED (L)	REFERENCE DENSITY ρ_r(kg/L)	(ρ/ρ_r) MAX (%)	DENSITY OF POURING (kg/L)	FIRST FREQ (Hz)	ACCEL (g)	VOLUME (L)	DENSITY ρ(kg/L)	SECOND FREQ (Hz)	ACCEL (g)	VOLUME (L)	DENSITY ρ(kg/L)	THIRD FREQ (Hz)	DENSITY ρ(kg/L)	SEPARATION OF SIZES	DUST
1	SAND-BUNDLES NOT INCLUDED	6.65	4.30	1.932	87.0	1.55	60	4	3.95	1.680							-	
2	SAND	7.52	4.83	1.932	89.1	1.56	30	4	4.40	1.710	60	4	4.38	1.715	120	1.72	-	3
3	SAND	6.76	4.36	1.932	89.0	1.55	150	4	3.92	1.72	70	4	3.92	1.72	25	1.72	-	
4	FINE GLASS (0.002 0.3mm dia)	6.60	4.12	1.780	97.8	1.60	25	4	3.89	1.70	90	4	3.80	1.73	180	1.74	LAYERS	3
5	FINE GLASS (0.002 0.3mm dia)	6.62	4.11	1.780	98.9	1.61	100	4	3.79	1.75	45	4	3.77	1.76			LAYERS	
6	GLASS BEADS (0.8 1.2mm dia)	8.17	4.20	2.221	91.4	1.94	40	4	4.04	2.02	110	4	4.02	2.03			-	1
7	A_2O_3 POWDER	TEST ABANDONED DUE TO EXCESSIVE DUST FORMATION																5
8	SINTERED BAUXITE	11.63	5.22	2.90	82.1	2.23	50	2	4.97	2.34	50	4	4.88	2.38				2
9	INTERPROP	8.69	4.75	2.38	83.6	1.83	50	2	4.39	1.98	50	4	4.36	1.99				2
10	ZIRCON	13.08	4.75	4.04	77.2	2.75	50	2	4.42	2.96	50	4	4.19	3.12				3
11	RUTILE	11.76	4.79	2.85	95.4	2.46	50	2	4.70	2.69	50	4	4.64	2.72				3
12	R-Z-G[2]	8.56	5.65	2.35	80.4	1.59	50	2	4.86	1.85	50	4	4.75	1.89				4
13	ZIRCOX S1702	12.01	6.37	4.00	65.8	1.89	50	2	5.96	2.02	50	4	4.57	2.63			VOIDS	3
14	GLASS BEADS	8.53	4.79	2.33	81.8	1.78	50	2	4.57	1.86	50	4	4.51	1.89				1
15	STEEL SHOT 0.8 - 1.2 mm	22.5	5.15	7.79	60.8	4.46	50	2	4.90	4.68	5	4	4.88	4.70				0

1. DUST IS RATED ON A SCALE FROM 0 (NO DUST) TO 5 (DUST CLOUD)
2. RUTILE - ZIRCON - GARNET COMBINATION
3. ACCELERATION IS GIVEN AS A PEAK-TO-PEAK VALUE

TABLE II

PROPERTIES OF PARTICULATES

NO.	PARTICULATE OR SOLID MATERIAL	TEST PRESSURE MPa	ν	E_p GPa	β GPa	E_p/E_t (1)	STRENGTH (2) δu (MPa)
	PARTICULATES						
1	WEDRON SAND	12.0	0.32	457	423	0.0042	*
2	GLASS BEADS 0.6-0.9	12.0	0.40	283	472	0.0026	32
3	GLASS BEADS 1.0-1.2	12.0	0.35	297	330	0.0027	27
4	GLASS BEADS 1.4-1.68	12.0	0.40	303	505	0.0028	27
5	PROTOTYPE GLASS BEADS	12.0	0.41	337	624	0.0031	27
6	STEEL SHOT	12.0	0.29	5,615	4,455	0.0065	*
7	CRUSHED BAUXITE	12.0	0.33	43	83	0.0008	14
8	INTERPROP	10.0	0.30	336	281	0.0031	*
9	SINTERED BAUXITE	10.0	0.34	285	297	0.0026	*
10	RUTILE	10.0	0.33	238	233	0.0022	*
11	ZIRCON	10.0	0.41	152	282	0.0014	*
12	ZIRCOX 51702	10.0	0.30	36	30	0.0003	12
13	COMBINATION R-Z-G	10.0	0.31	46	40	0.0004	14
	PARTICULATE WITH BUNDLE						
8	WEDRON SAND	9.7	0.26	1,662	1,151	0.0166	
9	GLASS BEADS 0.6-0.9	9.7	0.18	2,337	1,220	0.0234	
10	GLASS BEADS 1.0-1.2	9.7	0.34	1,041	1,055	0.0104	

(1) E_t = 100,000 MPa - Young's modulus of titanium

(2) Asterisk designates strength of above 50 MPa or clear breakdown point was not observed.

(3) The shown values are for illustration only as they vary widely with composition and treatment.

(4) Values quoted in Reference 4 for pressure of up to 0.2 MPa.

(5) Shear modulus can be calculated as $G = E/2\ (1 + \nu)$

TABLE III

LONG TERM SETTLEMENT OF PARTICULATE

PARTICULATE	STRAIN ($X10^6$)			CREEP EQUATION COEFFICIENTS(1)	
	FIRST 100 hr	100 hr 500 YEARS	0 TO 500 YEARS	A $X10^6$	B $X10^6$
GLASS BEADS	120	127	247	76.1	11.1
INTERPROP	50	136	186	22.9	10.7
SAND	167	54	221	144.3	5.0
ZIRCON	121	105	226	75.9	9.8
R-Z-G	69	96	165	33.6	8.6
RUTILE	271	91	362	237.3	8.2
SINTERED BAUXITE	33	144	177	5.0	11.3
ZIRCOX S1702	5,600	15,369	20,969	-1,150.3	1,471.3
STEEL SHOTS (2)	27			0.0	0.16
GLASS BEADS IN DDW(3)	74	69	143	10.55	1.65
GLASS BEADS IN SCSSS(4)	66	86	152	6.51	2.07

Notes:

1. Logarithmic distribution is assumed for all particulates except steel shots: Strain = A + B in (time)
2. Test indicates possibility of secondary creep in steel shots at 150°C. The equation used is:

   Strain = A + B x (time)

   Long term estimate is not realistic
3. Distilled de-ionized water
4. Standard Canadian Shield Saline Solution.

TABLE IV

PARTICULATE PACKING TEST RESULTS PROTOTYPE CONTAINER

Step	*Container Acceleration 1)*	*Frequency (Hz)*	*Duration (min)*	*Settlement (cm)*	*Level Above Basket (cm)*		*Comments*
					Before	*After*	
1	*0.5*	*40*	*7*	*2.5*	*2.5*	*0.5*	*22.7 kg of Beads Added*
2	*2.0*	*20*	*2*	*2.0*	*2.5*	*1.0*	*Centre Plate Showing (See Fig. 13)*
3	*2.0*	*40*	*2*	*3.0*	*1.0*	*-1.0*	*Basket Exposed (See Fig. 15)*
4	*2.0*	*70*	*2*	*1.0*	*4.5*	*4.0*	*45.4 kg of Beads Added Before Running*
5	*2.0*	*100*	*2*	*0.5*	*4.0*	*3.5*	
6	*4.0*	*40*	*0.5*	*0.5*	*3.5*	*3.0*	
7	*4.0*	*40*	*0.5*	*0.5*	*3.0*	*2.7*	*Lid Inserted*
8	*4.0*	*40*	*1.5*	*0.5*	*2.7*	*2.5*	

Notes:

1. *Sinusoidal acceleration was applied, symmetrical about zero. Values given are peak to peak, expressed in g's.*
2. *The height of particulate above basket is about 2.0 cm at the time of shipment.*

TABLE V

PROPERTIES OF PROTOTYPE TITANIUM

Property	Parent Metal	Weld Material	Minimum Required
Youngs Modulus (GPa)	99	120	107
Elongation (%)	35	17	20
Yield Strength (MPa)	262	279	275
Ultimate Strength	410	416	345

TABLE VI

RESULTS OF ANALYSIS OF PIE-SHAPED MODEL

Property	Locations			
	A	B	C	D
Radial Deformation (mm)	*-0.562*	*-0.510*	*-0.586*	*-0.200*
Average Radial Def. (mm)	*-0.544*			
Hoop Stress (MPa)	*-217.*	*-171.*	*-184.*	*-26.*
Radial Stress (MPa)	*-15.*	*-11.*	*-54.*	*-107.*

All stresses are for the outside surface and include bending moments.

See Figure 9 for locations

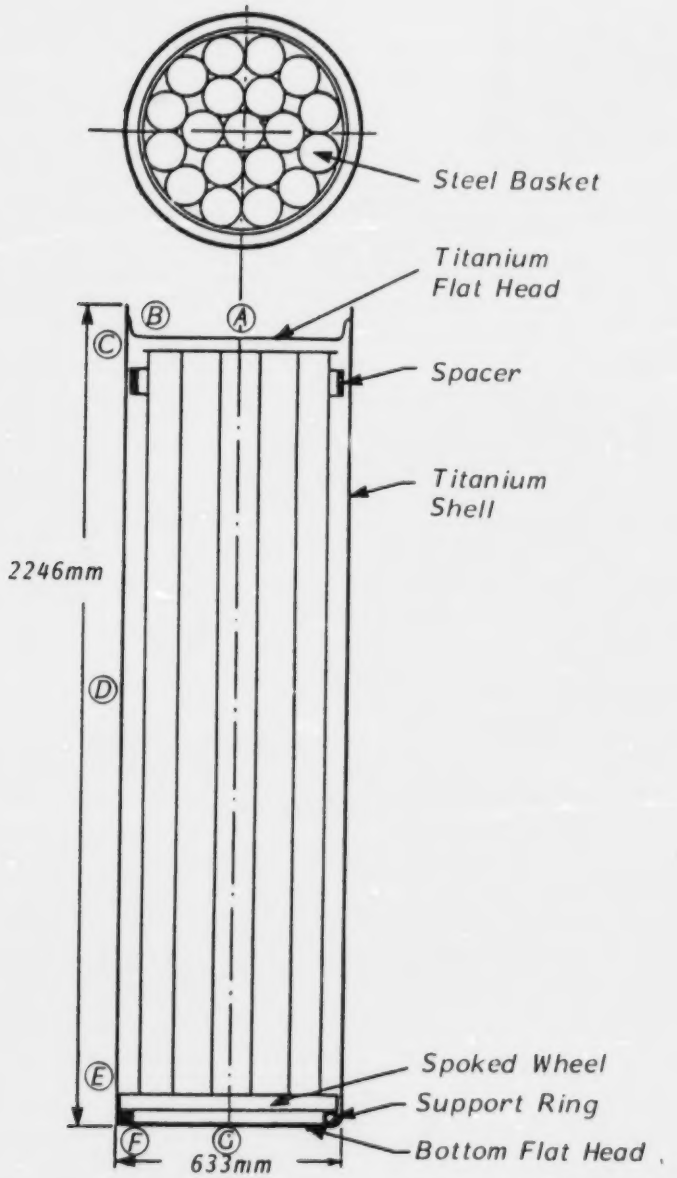
TABLE VII

STRAIN FROM ELASTIC TEST AND ANALYSIS

Location (1)	Strains (μm/m)			
	Test Results (2)		Analytical Results	
	Axial	Hoop	Axial	Hoop
A	*200*	*-220*	*1,400*	*1,300*
B	*-950*	*60*	*1,011*	*-400*
C	*-1460*	*-2210*	*-997*	*-1,636*
D	*-30*	*-1500*	*-650*	*-1,814*
E	*40*	*-1150*	*-84*	*-1,702*
F	*(3)*	*(3)*	*-70*	*-860*
G	*(3)*	*(3)*	*-45*	*-45*

Notes:

1. *See Figure 1 for locations.*
2. *Test results are obtained from the 125°C test.*
3. *These strains were not monitored during the test.*



○ *Locations for results in Table VII*

FIGURE 1

THIN-WALLED PARTICULATE-PACKED CONTAINER

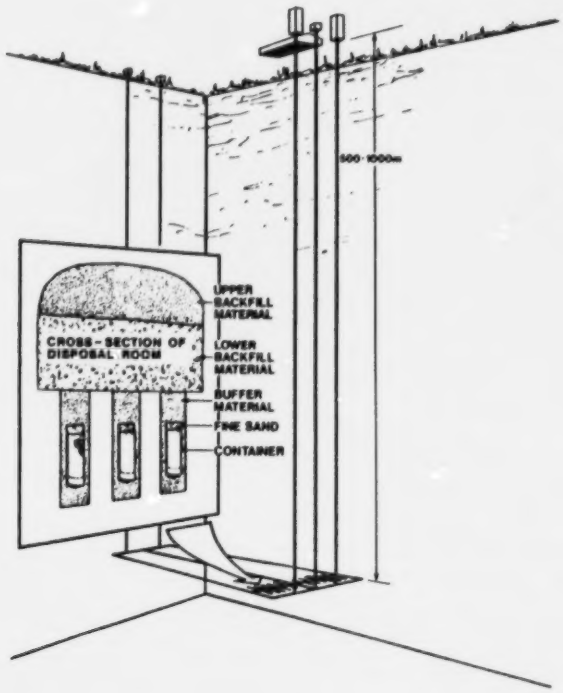


FIGURE 2
CONCEPTUAL VIEW OF NUCLEAR FUEL WASTE DISPOSAL VAULT

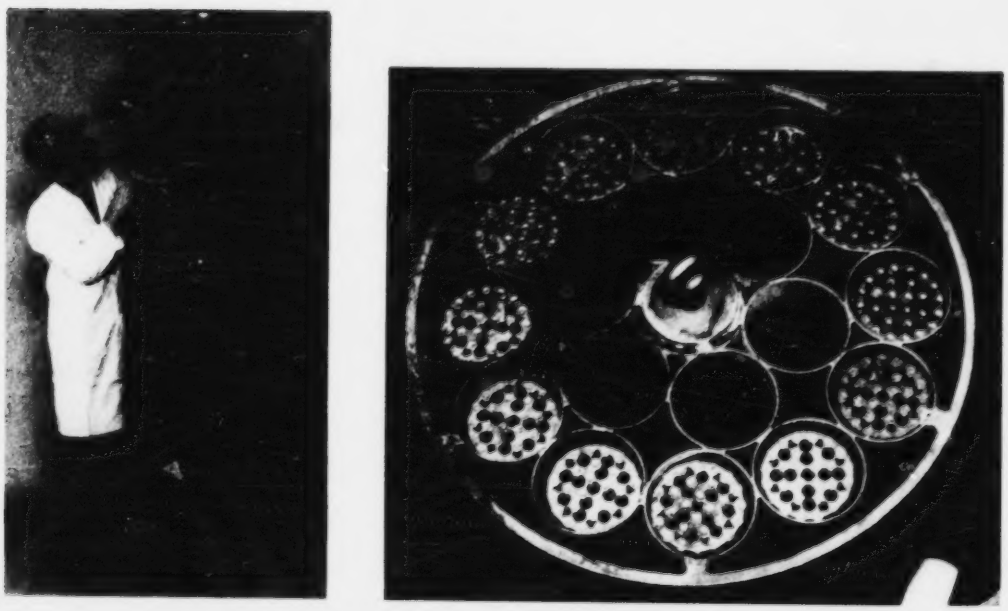


FIGURE 3
BASKET ARRANGEMENT

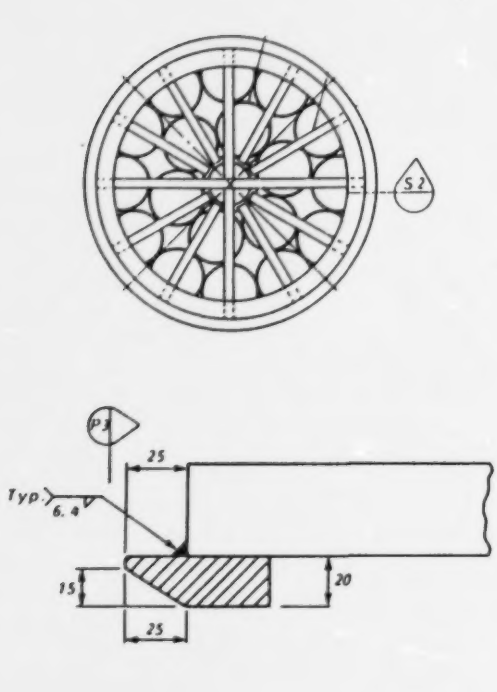


FIGURE 4
SPOKE WHEEL ARRANGEMENT

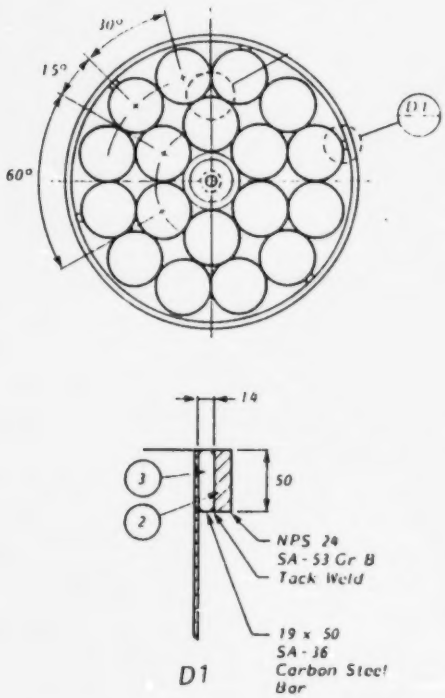


FIGURE 5
SPACER RING

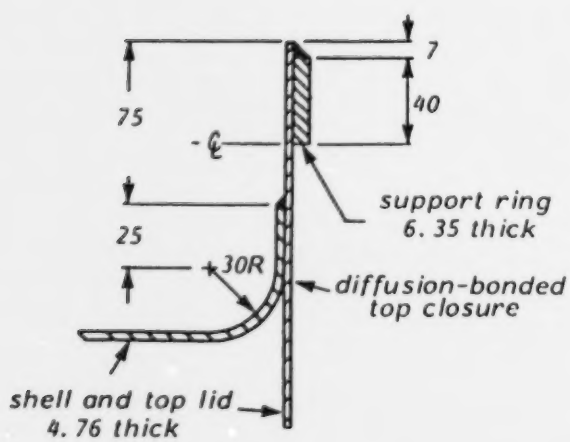
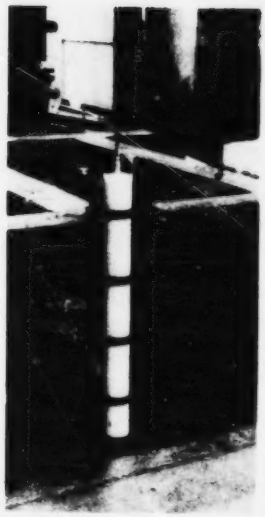


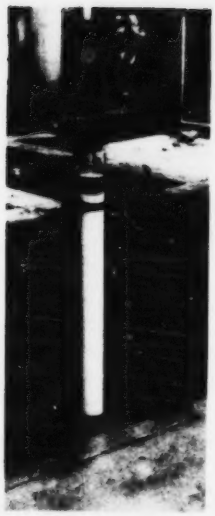
FIGURE 6
LIFTING ARRANGEMENT

FIGURE 7
SIMULATED BUNDLES

(a) Arrangemant Before Pouring



(b) Tube Filled With Particulate Before Vibratory Compaction



(c) After Vibratory Compaction

FIGURE 8
VIBRATORY COMPACTION TEST

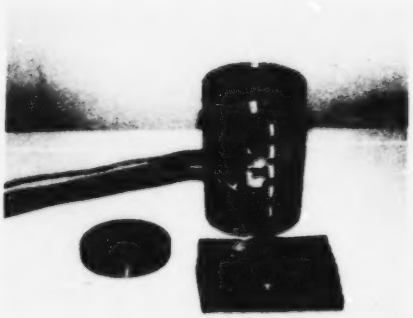


FIGURE 9
EQUIPMENT FOR PARTICULATE COMPRESSION TEST

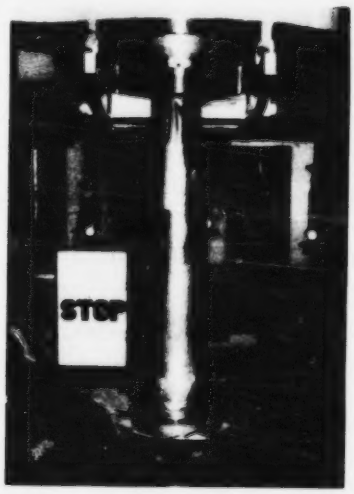
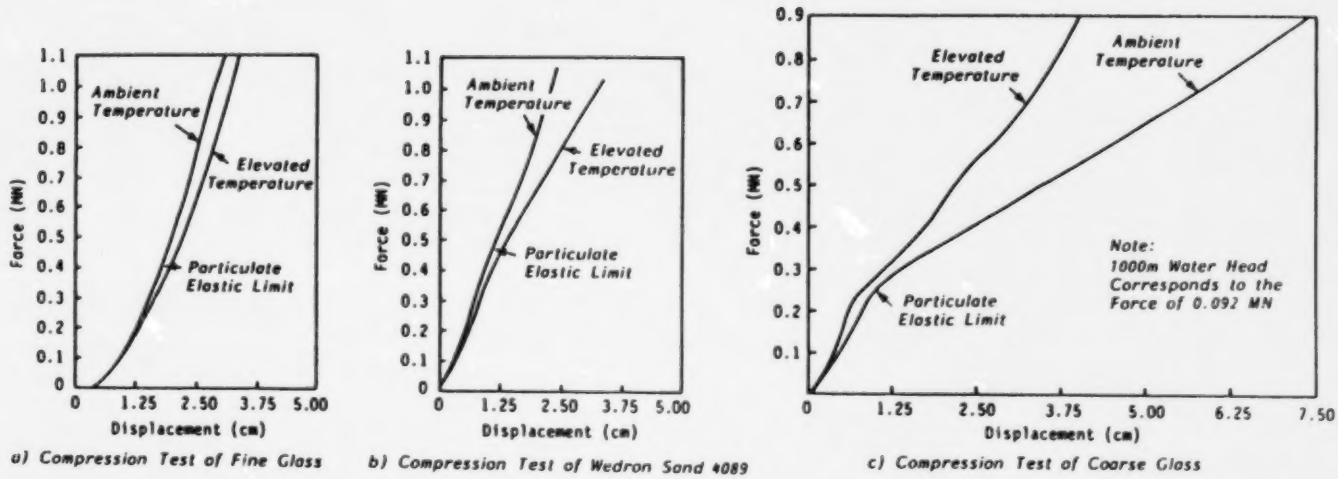


FIGURE 10
EQUIPMENT FOR TESTING OF PARTICULATE WITH BUNDLE

173426-RD



a) Compression Test of Fine Glass

b) Compression Test of Wedron Sand 4089

c) Compression Test of Coarse Glass

FIGURE 11

FORCE-DISPLACEMENT CURVES FOR COMPRESSION TESTS

FIGURE 12

CREEP-TEST STATION

173427-RD

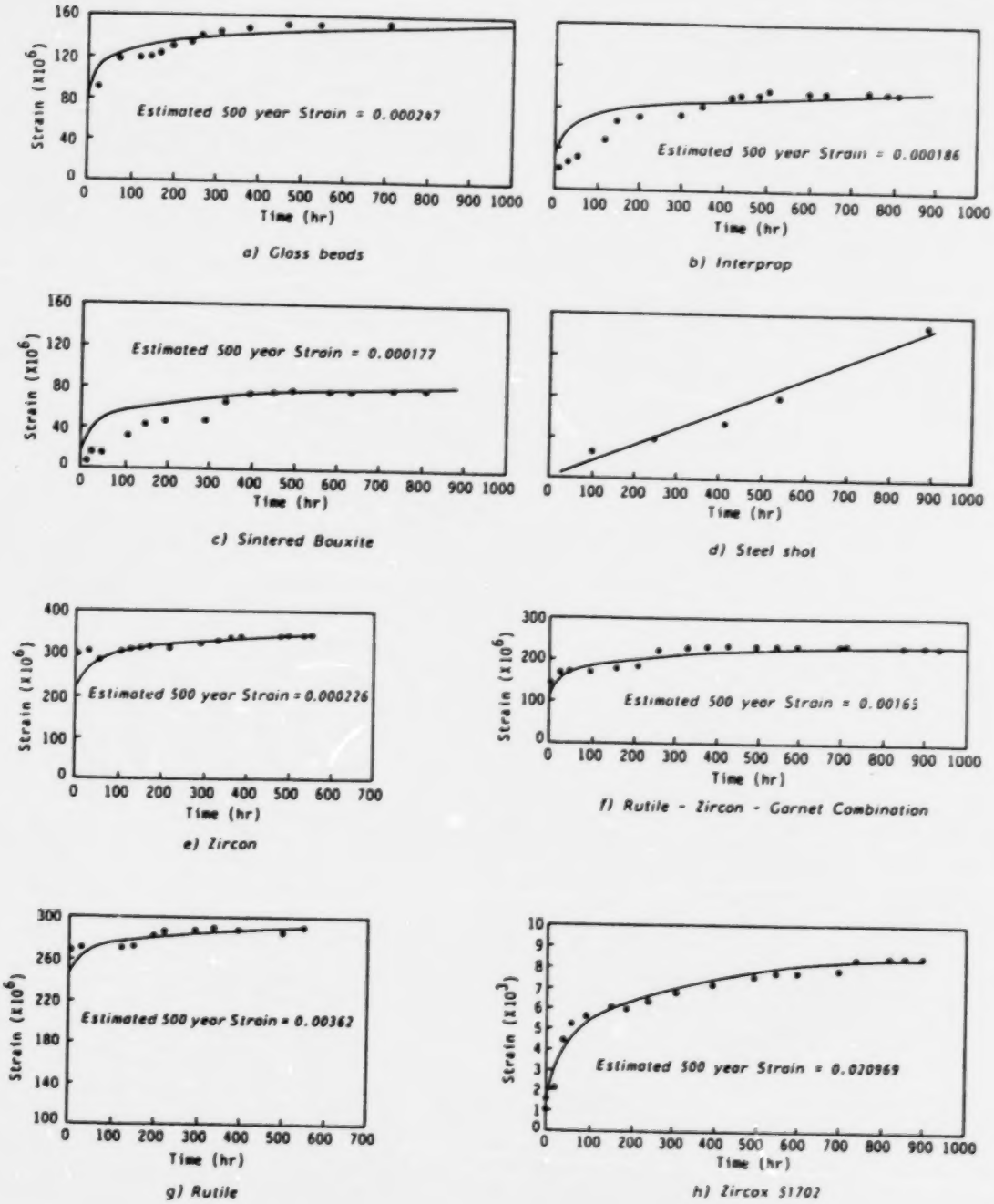
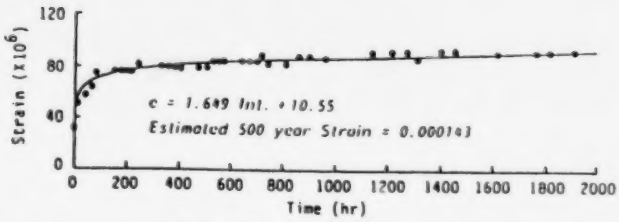
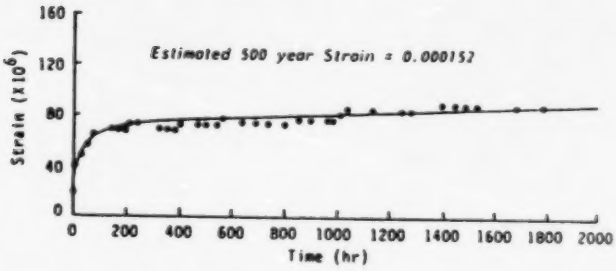

Strain (X10⁶)
Time (hr)
Estimated 500 year Strain = 0.000247
a) Glass beads
Estimated 500 year Strain = 0.000186
b) Interprop
Estimated 500 year Strain = 0.000177
c) Sintered Bauxite
d) Steel shot
Estimated 500 year Strain = 0.000226
e) Zircon
Estimated 500 year Strain = 0.00165
f) Rutile - Zircon - Garnet Combination
Estimated 500 year Strain = 0.00362
g) Rutile
Strain (X10³)
Estimated 500 year Strain = 0.010969
h) Zircox S1702

FIGURE 13
CREEP TEST RESULTS

173428-RD



a) Creep of Glass Beads in Di-ionized Water



b) Creep of Glass Beads in Standard Canadian Shield Saline Solution

FIGURE 14

CREEP OF GLASS BEADS IN SOLUTIONS

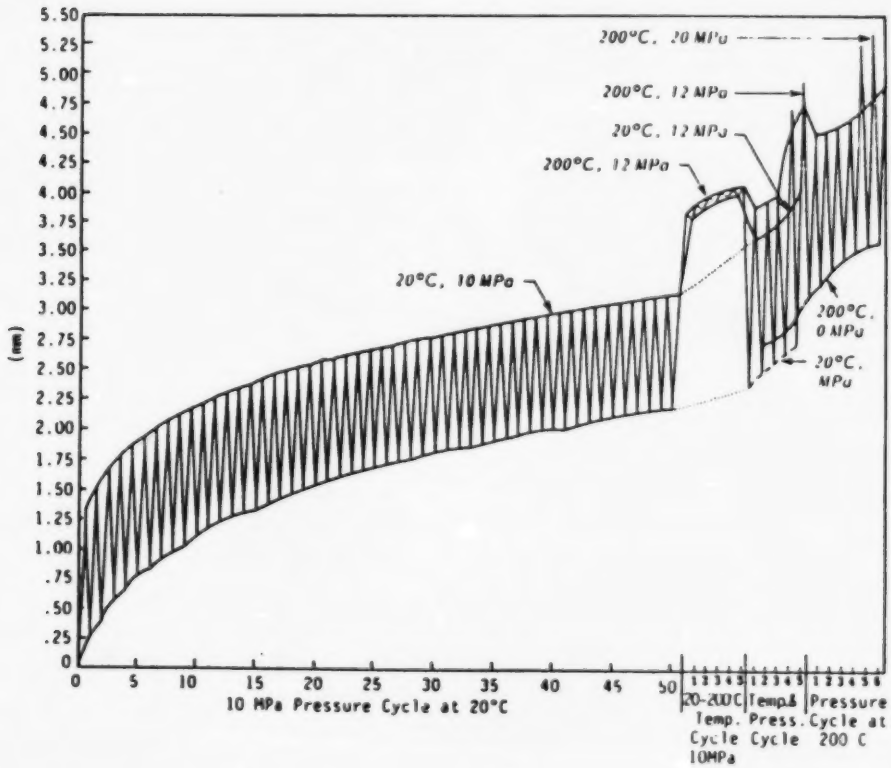


FIGURE 15

PRESSURE AND TEMPERATURE CYCLIC TEST OF GLASS BEADS

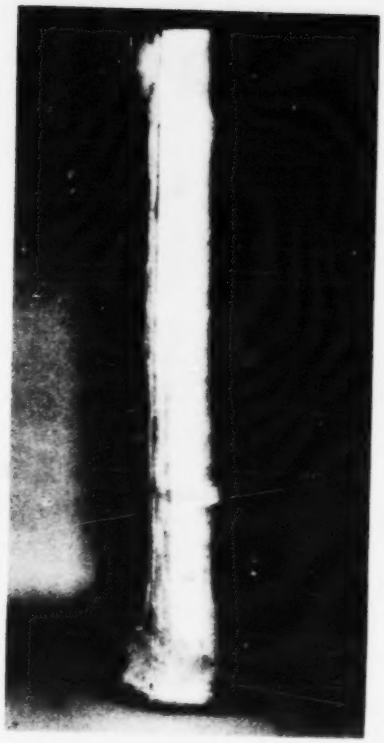


FIGURE 16
CONTAINER LAYOUT

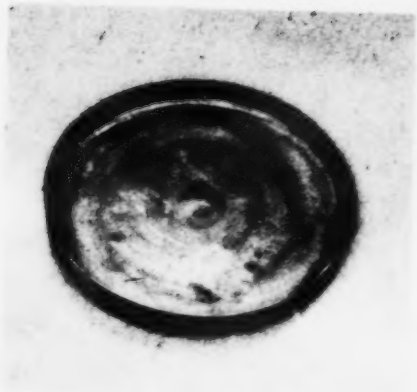


FIGURE 17
TOP LID

FIGURE 18
MID-HEIGHT
CIRCUMFERENTIAL WELD

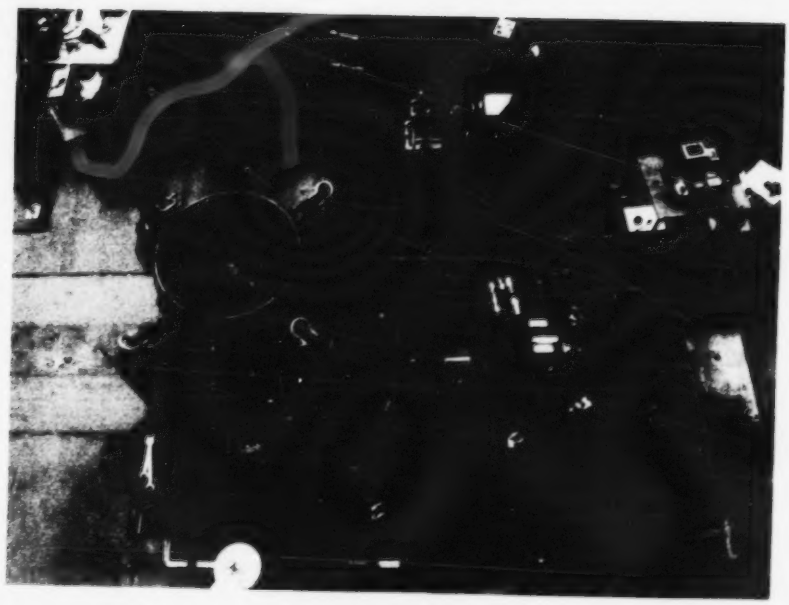
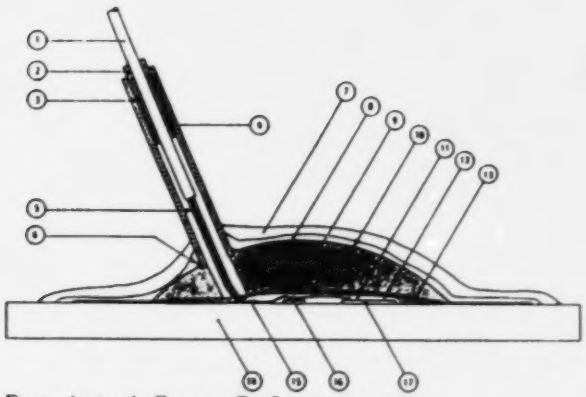


FIGURE 19
SHAKER TABLE



1 Leadwire Jacket
2 Copper Sleeve
3 Copper Tube
4 Crimp
5 Conductors
6 Silver Solder Joint
7 Silicon Sealant
8 M Coat 'C'
9 3145 RTV
10 Cap
11 M Bond 610 Coating
12 M Coat 'C'
13 Compound 111
14 Substrate
15 Nichrome Strip
16 Terminal Strip
17 Strain Gauge

Reprinted From Reference 13

FIGURE 20

SEALED CAP GAUGE PROTECTION SYSTEM

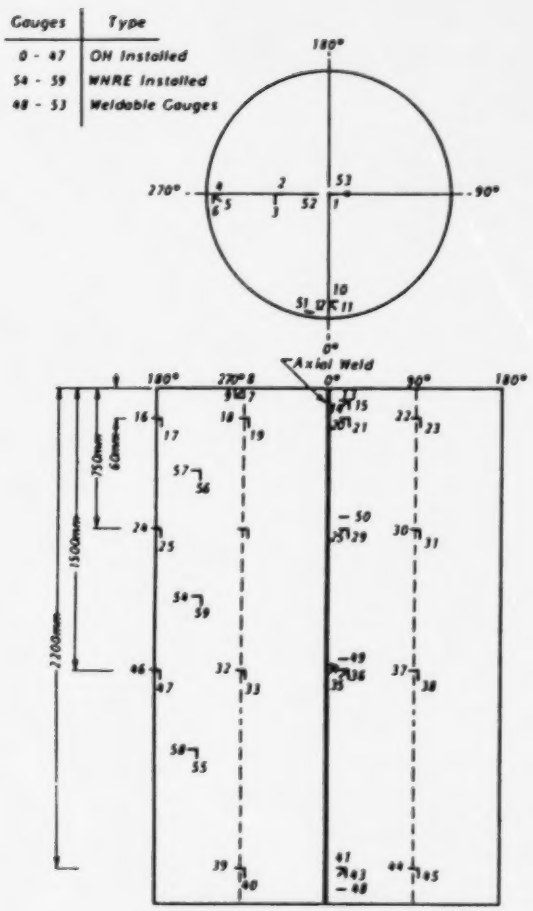


FIGURE 21

LOCATION OF STRAIN GAUGES
DURING INITIAL TESTS

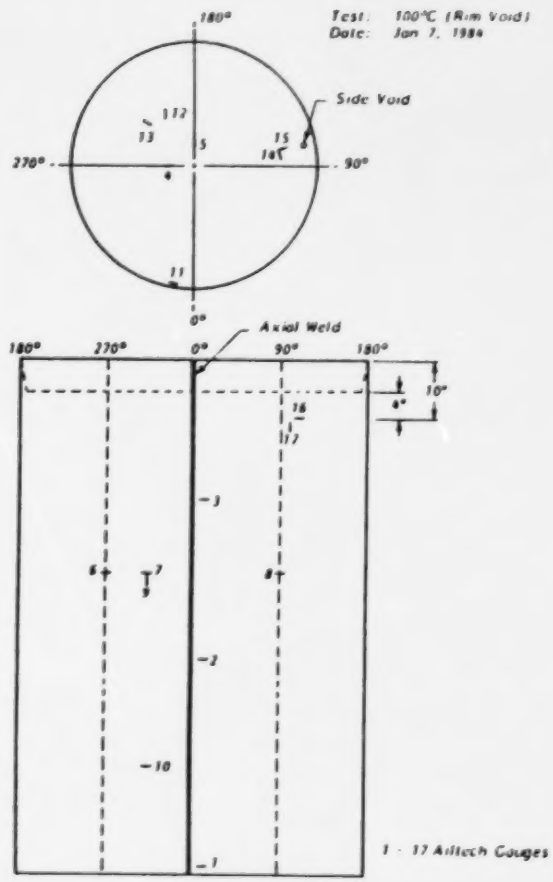


FIGURE 22

LOCATION OF STRAIN GAUGES
DURING TESTS WITH VOIDS

173431-RD

FIGURE 23
WNRE HYDROSTATIC
TEST FACILITY

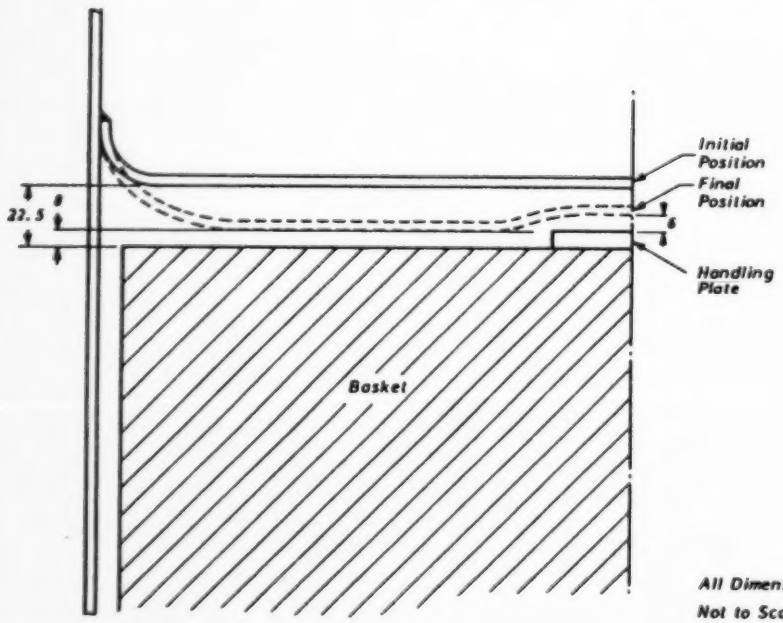
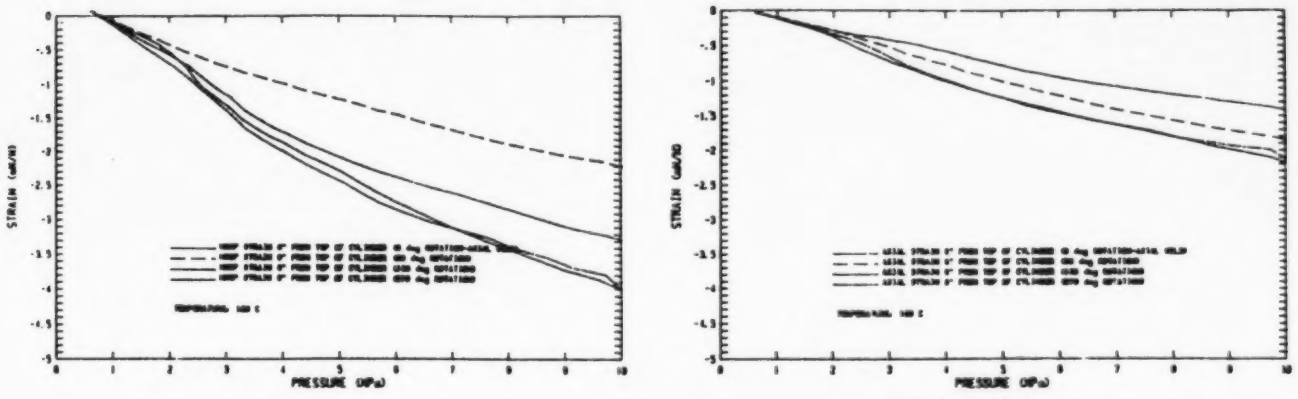


FIGURE 24
PERMANENT DEFORMATION OF TOP LID

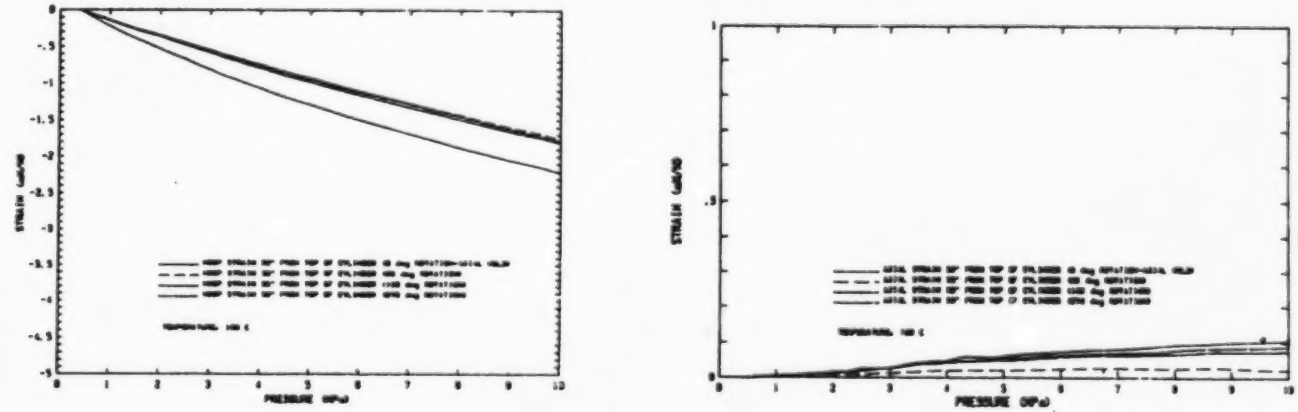
173432-RD



(a) Hoop Strain

(b) Axial Strain

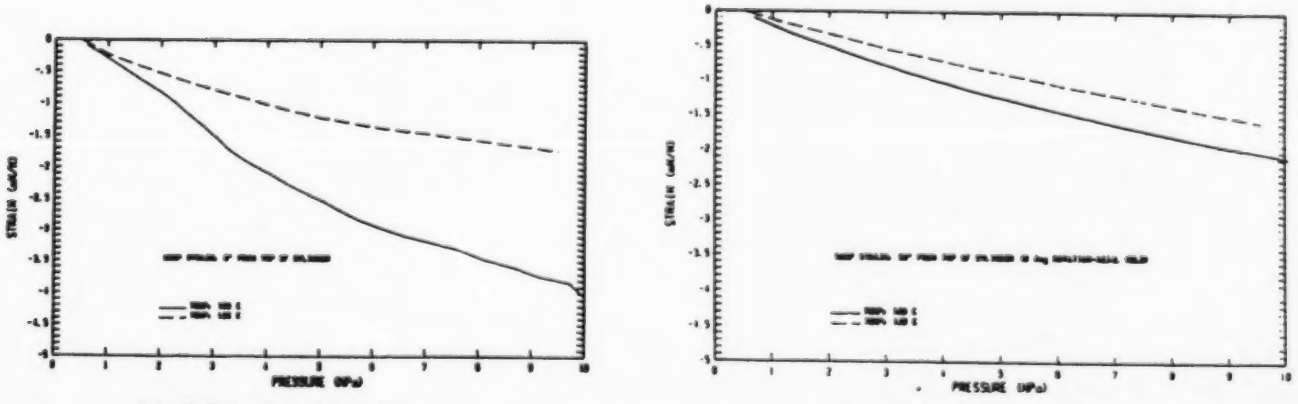
FIGURE 25
STRAIN IN CYLINDER BELOW TOP LID



(a) Hoop Strain

(b) Axial Strain

FIGURE 26
STRAINS IN CYLINDRICAL SHELL
AWAY FROM DISCONTINUITIES



(a) 6" Below Top of Cylinder

(b) 30" Below Top of Cylinder

FIGURE 27
STRAINS DURING 125° TEST - CYLINDRICAL SHELL

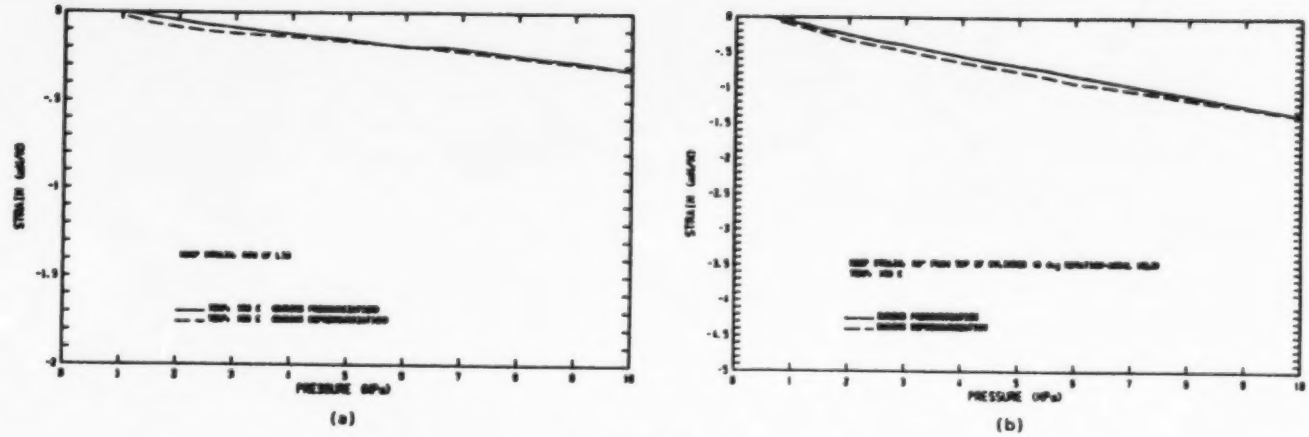


FIGURE 28
PRESSURE CYCLE DURING 150°C TEST

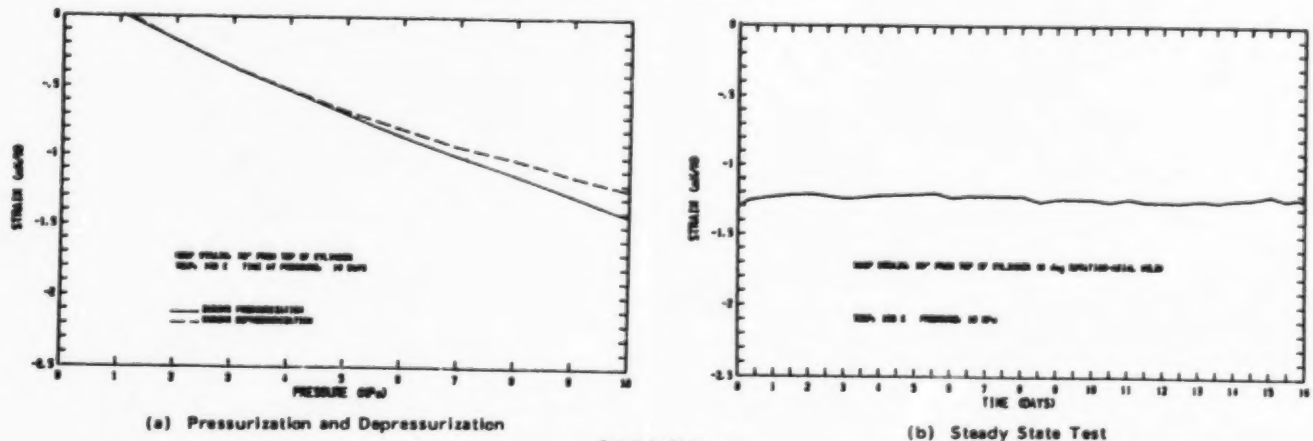


FIGURE 29
LONG TERM TEST RESULTS AWAY FROM DISCONTINUITIES

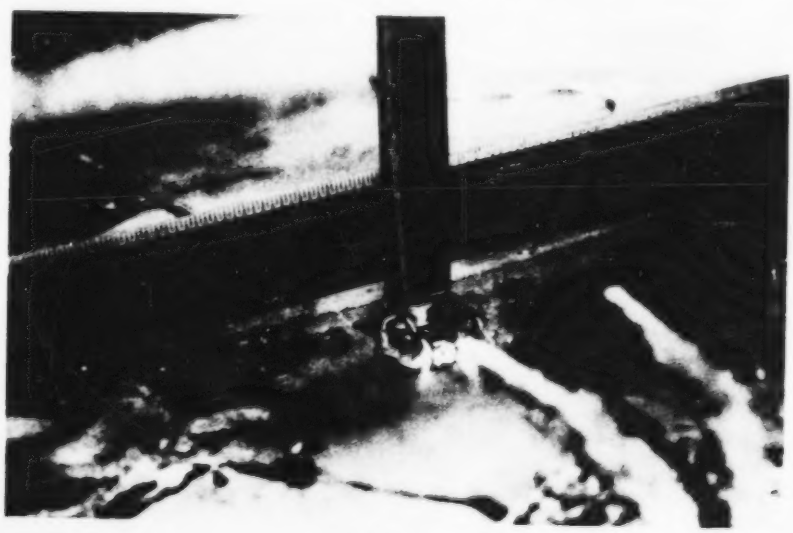
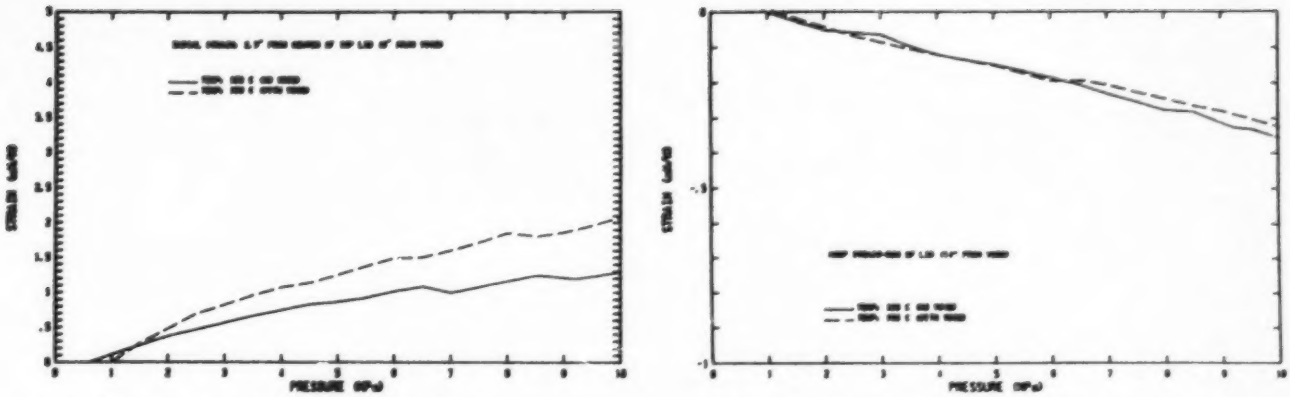


FIGURE 30
DEFORMATION OF TOP LID AFTER CENTRE VOID TEST

173434-RD



a) Strain At The Centre Void

b) Strain Away From Centre Void

FIGURE 31
STRAIN IN TOP LID AFTER CENTRE VOID TEST

FIGURE 32
LOCATION OF VOIDS

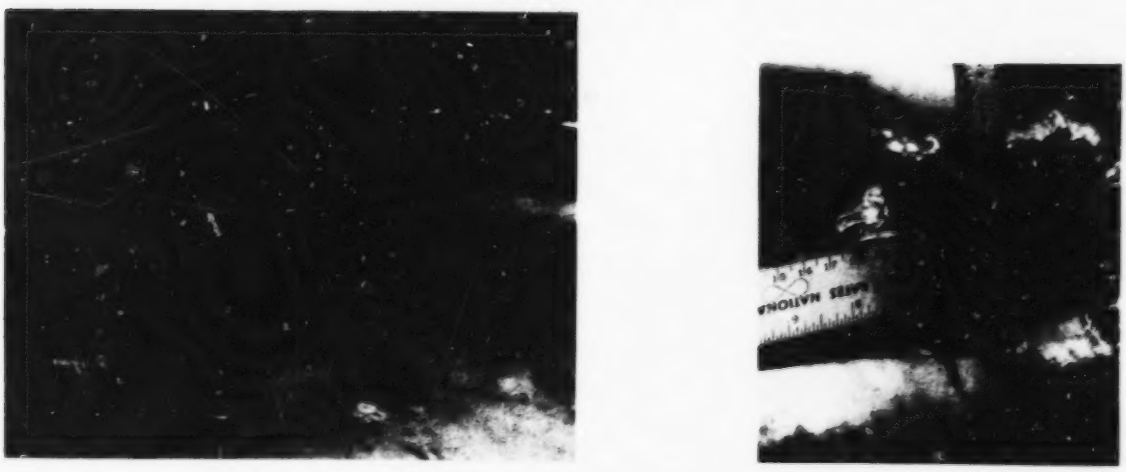


FIGURE 33
DEFORMATION OF TOP PLATE AT RIM VOID

173435-RD

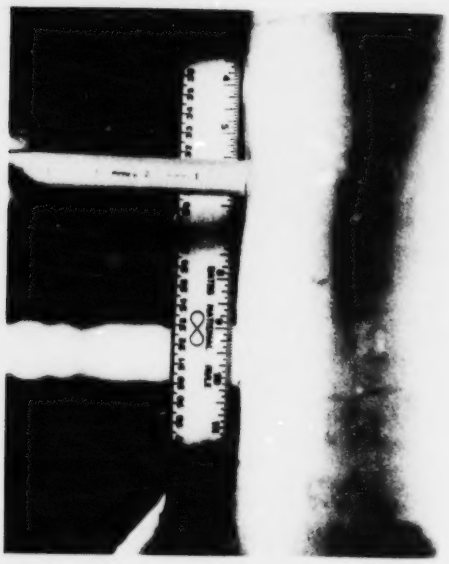
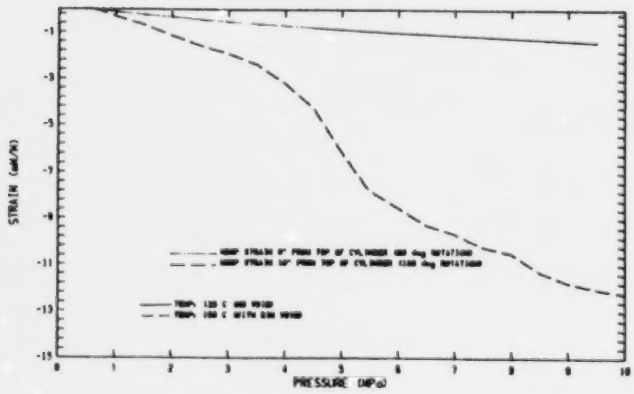
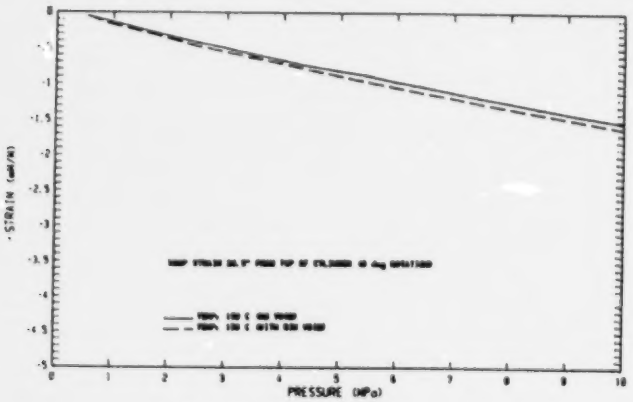


FIGURE 34
INSTABILITY OF CYLINDRICAL
SHELL DUE TO RIM VOID

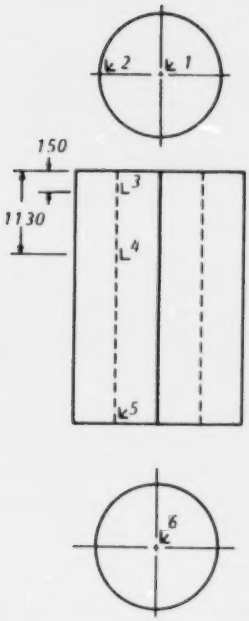


(a) Near Rim Void



(b) Away From Rim Void

FIGURE 35
COMPARISON OF STRAINS WITH
AND WITHOUT RIM VOID



(a) Strain-Gauge Locations

Strain Gauge	Principal Stresses (MPa)	
	Axial	Hoop
1	-0.3	-0.3
2	1.2	-3.905
3	1.7	-1.4
4	2.3	-0.4
5	20.8	-0.2
6	10.3	3.9

Sy = 200 MPa

(b) Test Results

FIGURE 36
LIFTING TEST

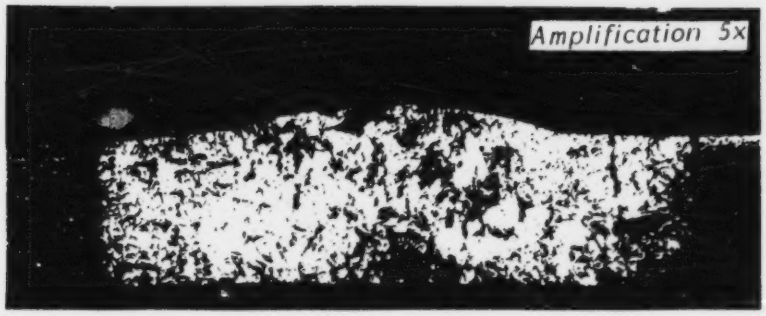


FIGURE 37
METALLURGICAL STRUCTURE OF WELD
AND PARENT METAL

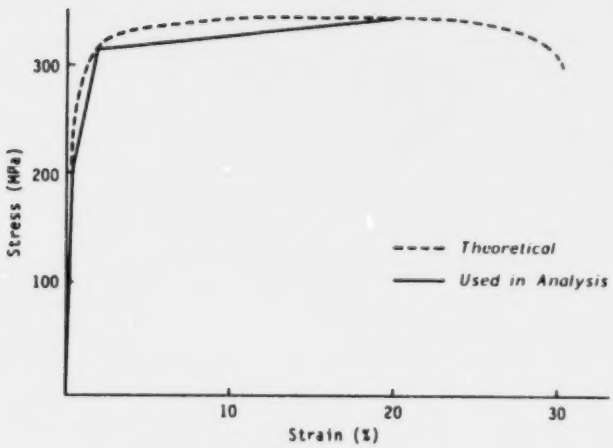


FIGURE 38
ASSUMED PLASTIC PROPERTIES OF TITANIUM

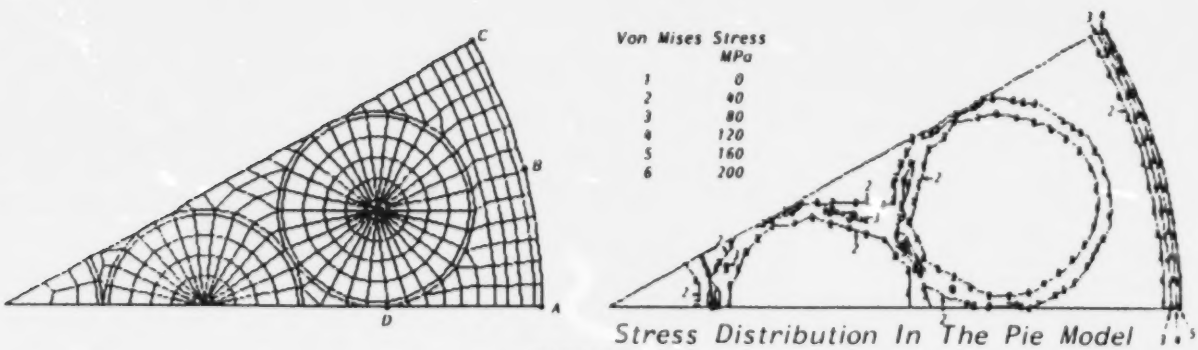


FIGURE 39
PIE-SHAPED MODEL OF TWPP CONTAINER

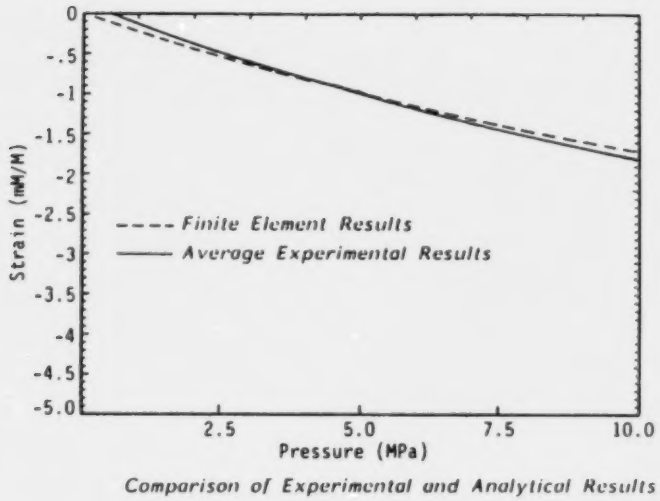


FIGURE 40
HOOP STRAINS IN CYLINDRICAL SHELL

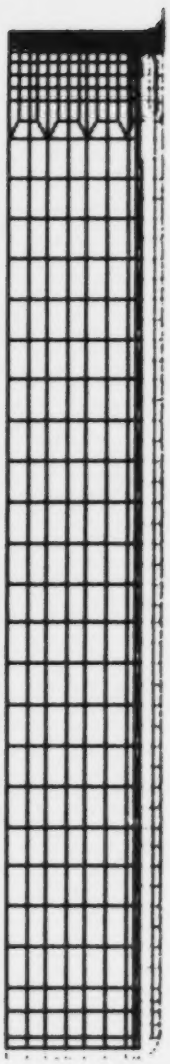


FIGURE 41
AXISYMMETRIC FINITE
ELEMENT MODEL

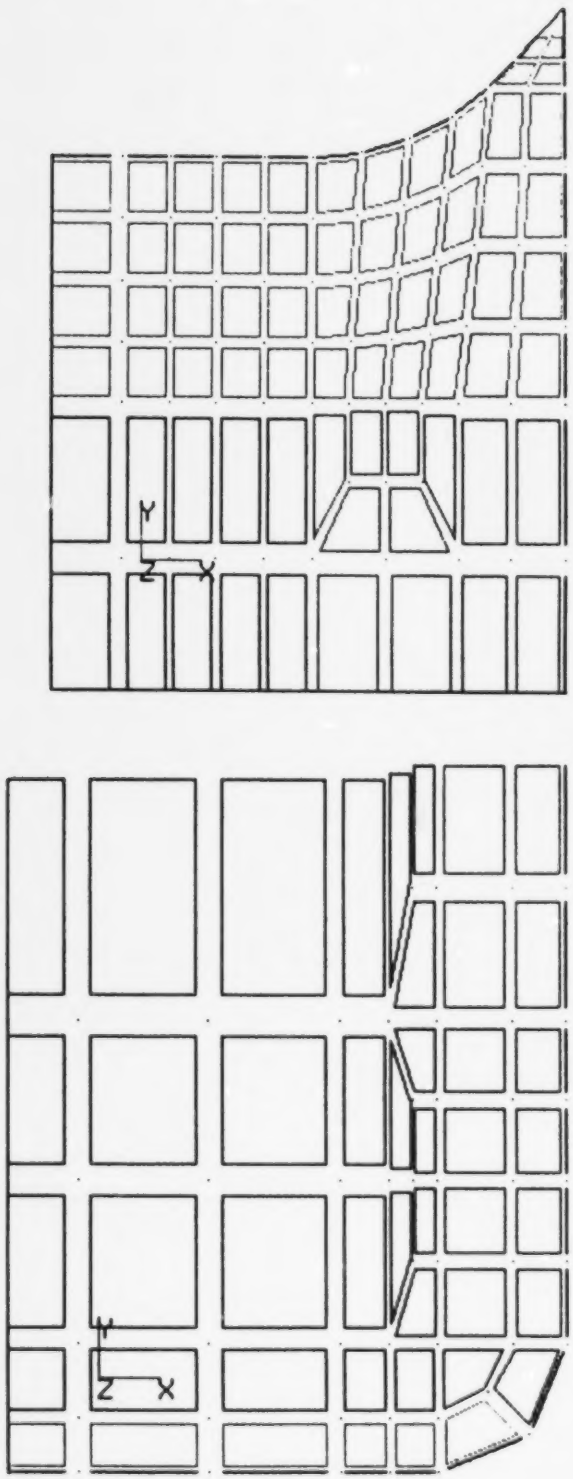


FIGURE 42
MODEL OF TOP AND BOTTOM AREAS

FIGURE 43
MODEL OF TOP VOID

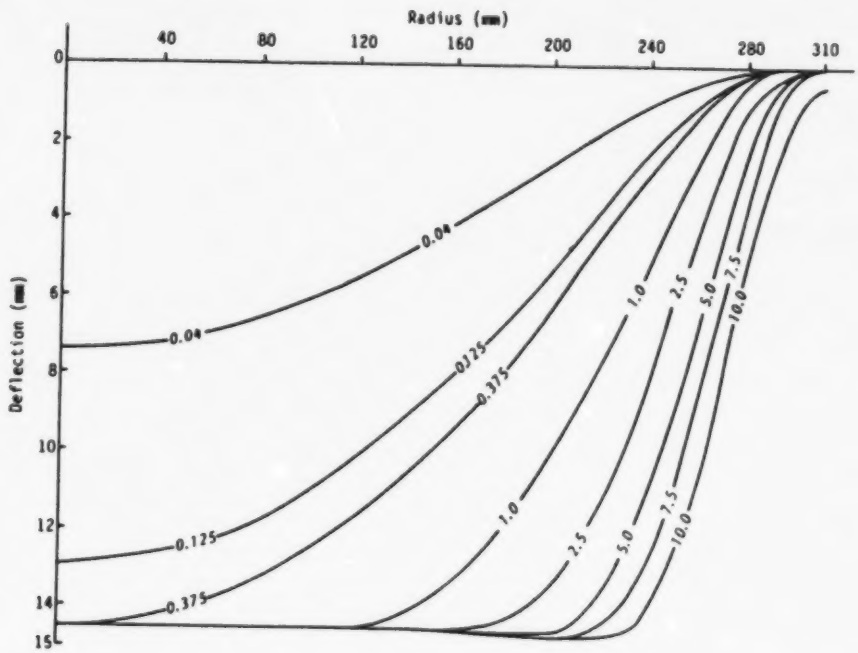


FIGURE 44
CLOSING OF TOP GAP

173440-RD

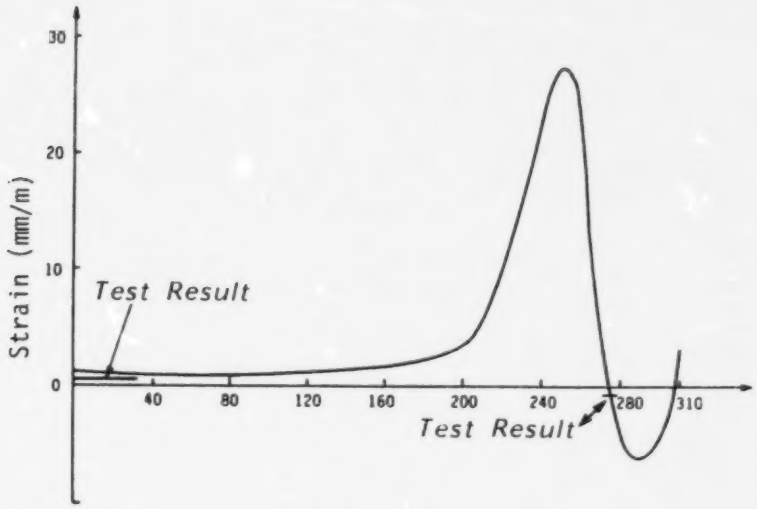


FIGURE 45
STRAIN IN TOP PLATE AT FULL PRESSURE

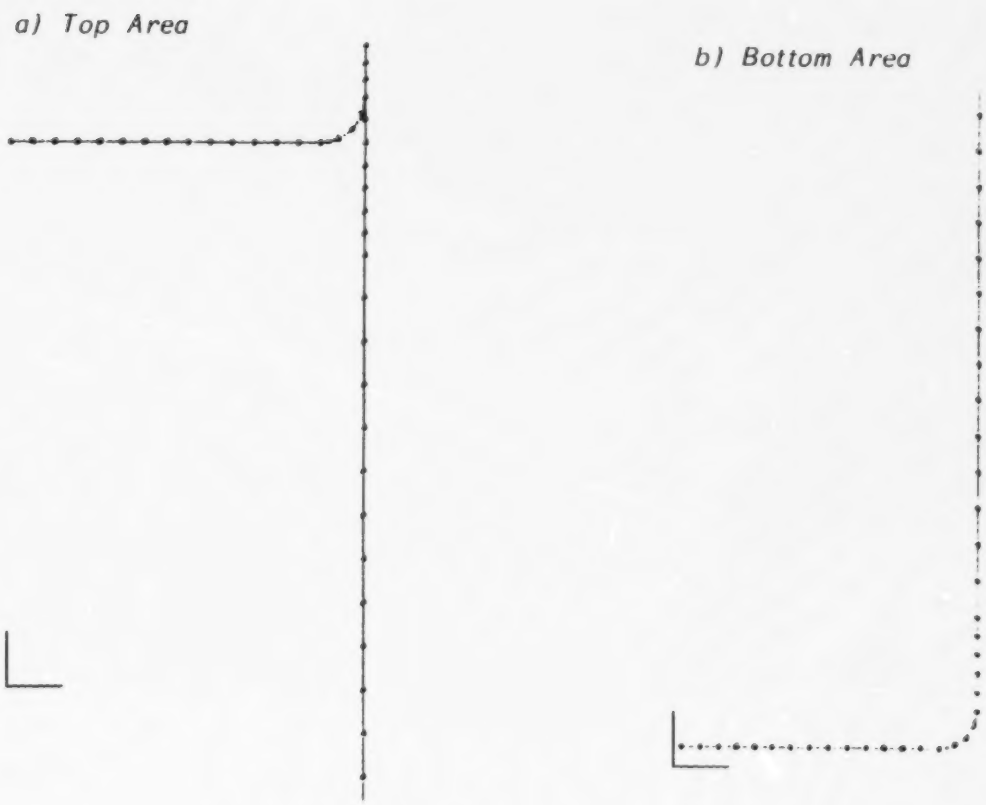


FIGURE 46
MODEL FOR ANALYSIS OF INTERNAL PRESSURE